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California Drought, An Update April 2008

Baryohay Davidoff

Fawzi Karajeh

Dean Reynolds

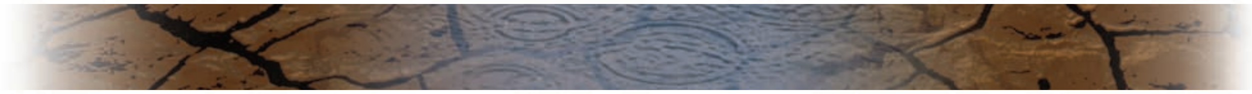
Eric Senter

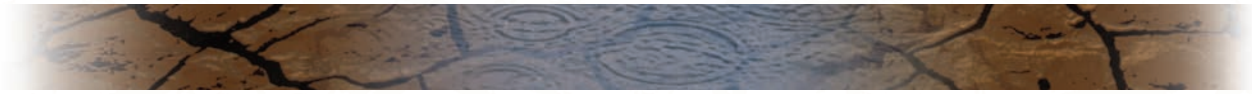
John Woodling

State of California • The Resources Agency • California Department of Water Resources

CALIFORNIA DROUGHT AN UPDATE

2008





CALIFORNIA DROUGHT, AN UPDATE

April 2008

Arnold Schwarzenegger
Governor
State of California

Mike Chrisman
Secretary for Resources
The Resources Agency

Lester A. Snow
Director
Department of Water Resources

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FOREWORD

Preparation of this report was initiated in response to dry conditions in 2007, when some Southern California communities experienced their driest year of record and when the Colorado River Basin continued in a period of unprecedented dryness. Just a few years earlier, Southern California experienced a regional drought in water years 1999 through 2002, during which time many Southern California communities experienced their then-driest period of record in the 2001-02 season. This report covers hydrologic conditions through Water Year 2007. As we near the end of the Spring 2008 rainy season, it appears that Water Year 2008 runoff in most of California's watersheds will again be below average.

Although 2007 was dry, a wet 2006 left a fortunate legacy of good storage conditions in the majority of California's reservoirs and groundwater basins. Thanks to past investments in the state's water infrastructure, serious impacts of last year's dry conditions were minimal for most water agencies, with depletion of stored supplies being the most widespread outcome of dry conditions. The devastating wildfires that laid siege to Southern California in 2007 and 2003, characterized as the costliest and most damaging wildfires in U.S. history, were the major impacts from a dry 2007 and from the prior Southern California regional drought.

As scientific research yields new insights into climate prediction and forecasting, we may some day be able to use such information to put in place longer-range response plans and to reduce drought's multi-faceted impacts. The purpose of this report is to update an earlier Department report on drought published on 2000, with special emphasis on advances in drought-related research. To this end, the report features contributed articles from climate scientists whose research covers a wide range of drought and climate change or variability topics. The report also provides updates on hydrologic conditions and selected resource management subjects since publication of the Department's 2000 report.

Lester A. Snow

Director, Department of Water Resources

This report was prepared by:
Jeanine Jones
Interstate Resources Manager

With data supplied by:
Baryohay Davidoff, Senior Land and Water Use Scientist
Fawzi Karajeh, Senior Land and Water Use Scientist
Dean Reynolds, Staff Land and Water Use Scientist
Eric Senter, Senior Engineering Geologist
John Woodling, Supervising Engineering Geologist

Production Services provided by:
Chris Sanchez

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CHAPTER 1

RECENT HYDROLOGIC CONDITIONS AND IMPACTS

CHAPTER 1
RECENT HYDROLOGIC CONDITIONS AND IMPACTS

Introduction

In 2000 the Department of Water Resources (DWR) published a report entitled Preparing for California's Next Drought, Changes Since 1987-92 (DWR, 2000a). That report provided input to the deliberations of the Governor's Advisory Drought Planning Panel, which released its Critical Water Shortage Contingency Plan (DWR, 2000b) later in 2000. This 2008 report on California drought reviews hydrologic conditions experienced since 2000, updates the status of selected water management activities having a bearing on drought preparedness, and highlights advances in hydroclimate research related to droughts. The particular focus of this report is illustrating advances in drought- and climate-related research. To this end, articles solicited from climate scientists whose work spans a broad spectrum of research topics form one chapter of the report.

California's most recent multi-year statewide drought was the six-year 1987-92 event. Parts of California saw dry conditions in the early 2000s, with Southern California experiencing a four-year regional drought from 1999 through 2002, during which time then-record low precipitation amounts were experienced. The most recent water year, water year 2007, was a dry year throughout California, with parts of Southern California once again setting new records for minimum annual precipitation. The Colorado River Basin, an important source of imported water for Southern California, continued in prolonged drought conditions.

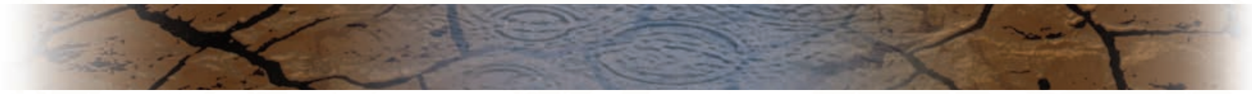
The first chapter of this report details dry hydrologic conditions subsequent to preparation of the Department's 2000 drought report, and describes actions taken in response to those hydrologic conditions. The chapter begins with a discussion of dry conditions in 2007, and then describes other dry periods in reverse chronological order. Chapter Two provides updates on selected changed conditions since publication of the 2000 report, focusing on actions of an institutional or programmatic nature. One major such action, for example, is voter approval of bond measures that have authorized billion-dollar state funding for grant programs that would, among other things, help local agencies improve their ability to cope with droughts. Chapter Three features contributed articles from climate scientists covering various aspects of recent research.

Water Year 2007

Water year 2007 was California's first dry year following a wet 2006, which left the state with generally good storage conditions in surface reservoirs and groundwater basins. Table 1 compares precipitation at selected locations during the immediately past precipitation season (July 1, 2006 through June 30, 2007) to annual precipitation during prior drought events. Parts of Southern California, including the City of Los Angeles, experienced record low precipitation during the past season. Northern California was also dry, although less so than the southern part of the state. The Northern Sierra precipitation accumulation factor, used by the Department to assess conditions in the Sacramento, Feather, Yuba, and American River Basins, was 73 percent of average for the water year. As of July 1, 2007 (when the new precipitation year began), statewide runoff was 55 percent of average for that time, with statewide reservoir storage being at 90 percent of average.

THE WATER YEAR

Agencies such as the Department or the U.S. Geological Survey report hydrologic data on a water year basis. The water year extends from October 1st through September 30th. Water year 2007, for example, spanned from October 1, 2006 through September 30, 2007. The (water year) 1987-92 drought corresponds to the calendar period of fall 1986 through summer 1992. Hydrologic data contained in this report are presented in terms of water years. Water project delivery data (e.g. State Water Project deliveries) are presented on a calendar year basis. Precipitation data are reported by the National Weather Service (NWS) based on an annual season of July 1st to June 30th. When this report refers to annual precipitation amounts, it is implicit that the data are based on the NWS reporting season.



Single dry year impacts to larger water agencies are normally minor, thanks to California's extensive system of water infrastructure and water management programs. A single dry year is also not likely to result in widespread problems for at-risk small water systems and private residential well owners relying on marginal groundwater sources, although experience indicates that some impacts will occur. The North Coast and a few isolated areas in the Sierra Nevada foothills were the dominant locations of 2007 small water system shortage problems. Impacts to dryland agriculture (livestock grazing, non-irrigated hay and grain crops) are a typical feature of a single dry year. A table of federal agricultural drought emergency declarations for 2007 is included in Appendix 1. The largest economic threat from a single dry year is usually the risk of wildfire damages, a risk that becomes increasingly great as residential development continues to occur at the wildland/urban interface. This risk was manifested in October 2007, when a combination of dry vegetation and Santa Ana winds created conditions favorable for a massive outbreak of wildfires in Southern California (Figure 1).

The largest urbanized area where mandatory numerical water use reductions were called for in 2007 was the Sonoma County Water Agency (SCWA) service area. There, the State Water Resources Control Board had ordered SCWA to reduce its Russian River diversions by 15 percent as part of a Board order temporarily reducing instream flow requirements to conserve water in Lake Mendocino for fall chinook salmon spawning. SCWA in turn called for the cities in its service area, such as Santa Rosa and Sonoma, to achieve the 15 percent reduction.

Dry conditions exacerbated by late spring curtailment of State Water Project (SWP) exports to protect the Delta smelt led some water agencies, particularly urban agencies receiving supplies from the Delta, to call for voluntary conservation from their customers. Urban water suppliers calling for their customers to voluntarily reduce water use by specified amounts included San Diego County Water Authority (20 gallons per person), Los Angeles Department of Water and Power (10 percent), and Santa Clara Valley Water District (10 percent).

ENSO AND WATER CONDITIONS

El Niño and La Niña are the extremes of the El Niño/Southern Oscillation (ENSO) cycle, a coupled ocean-atmosphere phenomenon that causes global climate variability on interannual time scales. The equatorial Pacific Ocean is warmer than average during El Niño events and cooler than average during La Niña events. Generally, these events begin developing in the late spring in the Northern Hemisphere and reach their maximum strengths during December-February. Although the events often persist for about a year, their duration can vary significantly. The impacts of a particular ENSO event depends on its relative strength, and the impacts vary with geographic location. ENSO events are only one of many factors influencing local climatic conditions, and in many years there is no ENSO signal (termed neutral conditions).

The National Oceanic and Atmospheric Administration (NOAA) has established an index to define El Niño and La Niña events, based on temperature conditions in a region of the equatorial Pacific Ocean known as the Niño 3.4 region, an area bounded by longitudes 120W-170W and latitudes 5N-5S. Using these criteria, moderate La Niña conditions were present in the latter part of 2007. NOAA's definition of these conditions is:

El Niño: A phenomenon in the equatorial Pacific Ocean characterized by a positive sea surface temperature departure from normal (for the 1971-2000 base period) in the Niño 3.4 region greater than or equal in magnitude to 0.5 degrees C, averaged over three consecutive months.

La Niña: A phenomenon in the equatorial Pacific Ocean characterized by a negative sea surface temperature departure from normal (for the 1971-2000 base period) in the Niño 3.4 region greater than or equal in magnitude to 0.5 degrees C, averaged over three consecutive months.

Others have defined ENSO conditions based on the Southern Oscillation Index (SOI), a measurement of atmospheric conditions, or based on a combination of several criteria. Table 2, based on information from the Western Regional Climate Center, is an example of ENSO conditions based on the SOI. Generally, El Niño conditions are associated with drier winters in the Pacific Northwest and wetter conditions in the Southwest and Southern California, but do not yield a strong signal as to wetter/dryer in Northern and Central California. La Niña conditions typically yield the opposite effect. ENSO events are not in and of themselves key triggers for forecasting water supply or flood risk conditions, but are a piece of information that can be considered in making forecasts.

Table 1
Precipitation at Selected Locations (July 1 to June 30 precipitation in inches)

Time Period	Location											
	Eureka	**Redding**	**San Francisco**	**Sacramento**	**Fresno**	**Santa Barbara**	**Bakersfield**	**Long Beach Civic Center**	**Los Angeles**	**San Diego**	**Riverside**	**Death Valley**
Average Annual	39.55	37.00	20.26	18.20	10.95	16.32	6.23	12.11	14.89	10.21	10.09	2.28
2006-07	36.52	22.73	11.66	12.22	6.06	7.24	3.06	2.12	3.21	3.83	1.70	1.83
1976-77 drought												
1975-76	33.55	22.90	7.73	7.25	8.18	7.83	4.37	4.98	7.22	9.11	7.89	3.44
1976-77	17.56	20.97	11.05	7.53	7.61	15.90	4.19	8.78	12.31	8.08	8.70	2.74
1987-92 drought												
1986-87	27.93	21.48	10.74	12.81	9.32	10.91	5.58	7.59	7.66	9.61	6.65	1.96
1987-88	32.31	30.22	14.34	15.37	8.07	14.06	5.55	8.25	12.48	13.18	9.27	5.78
1988-89	34.88	33.53	13.77	15.13	8.73	8.76	3.74	6.09	8.08	5.65	6.94	0.68
1989-90	26.83	29.93	11.87	19.40	9.45	5.76	3.30	6.39	7.35	7.84	5.80	0.57
1990-91	25.11	22.07	13.47	14.73	9.77	16.74	5.95	9.99	11.47	11.79	10.53	1.77
1991-92	21.92	28.42	18.21	16.68	11.05	18.33	7.00	13.76	21.00	12.93	11.18	2.59
1999-2002 drought												
1998-99	49.99	30.87	16.91	15.27	7.01	12.04	6.96	8.47	9.09	6.71	5.86	1.24
1999-2000	36.44	34.28	20.69	23.74	12.91	25.10	5.15	6.60	11.57	5.76	5.19	1.23
2000-01	22.84	30.15	16.24	17.31	10.56	23.68	5.77	10.90	17.94	8.58	7.35	2.70
2001-02	40.66	28.86	19.32	17.08	7.03	9.07	3.59	2.21	4.42	2.99	3.30	0.46

Other urban agencies – such as the Metropolitan Water District (MWD), City of Long Beach, East Bay Municipal Utility District, and Monterey Peninsula Water Management District – asked their customers to take specific conservation measures or instituted new public awareness campaigns. Reducing urban outdoor water use for lawns and landscaping was a particular focus of many agencies' public awareness campaigns, especially in Southern California.

In May 2007, the federal District Court in Natural Resources Defense Council v. Kempthorne, No. 05-1207 (E.D. Cal. May 25, 2007) upheld a challenge to a U.S. Fish and Wildlife Service (USFWS) Delta smelt biological opinion for SWP and Central Valley Project (CVP) diversions in the Delta. The court called for implementation of an interim remedy to protect the Delta smelt while the USFWS developed a new biological opinion. The court's order establishing an interim remedy of reduced water project diversions from the Delta, to remain in place through June 20, 2008, was issued in December 2007. The Department estimated that the court's decision would result in delivery reductions to SWP contractors of 7-22 percent if 2008 is a dry year and 22-30 percent if 2008 is an average water year.

Delta smelt are usually found in areas of the Bay-Delta Estuary where the salinity is about 2,000 parts per million (ppm), although they have been found in areas where salinity is greater than 14,000 ppm.

Figure 1
2007 Southern California Wildfires

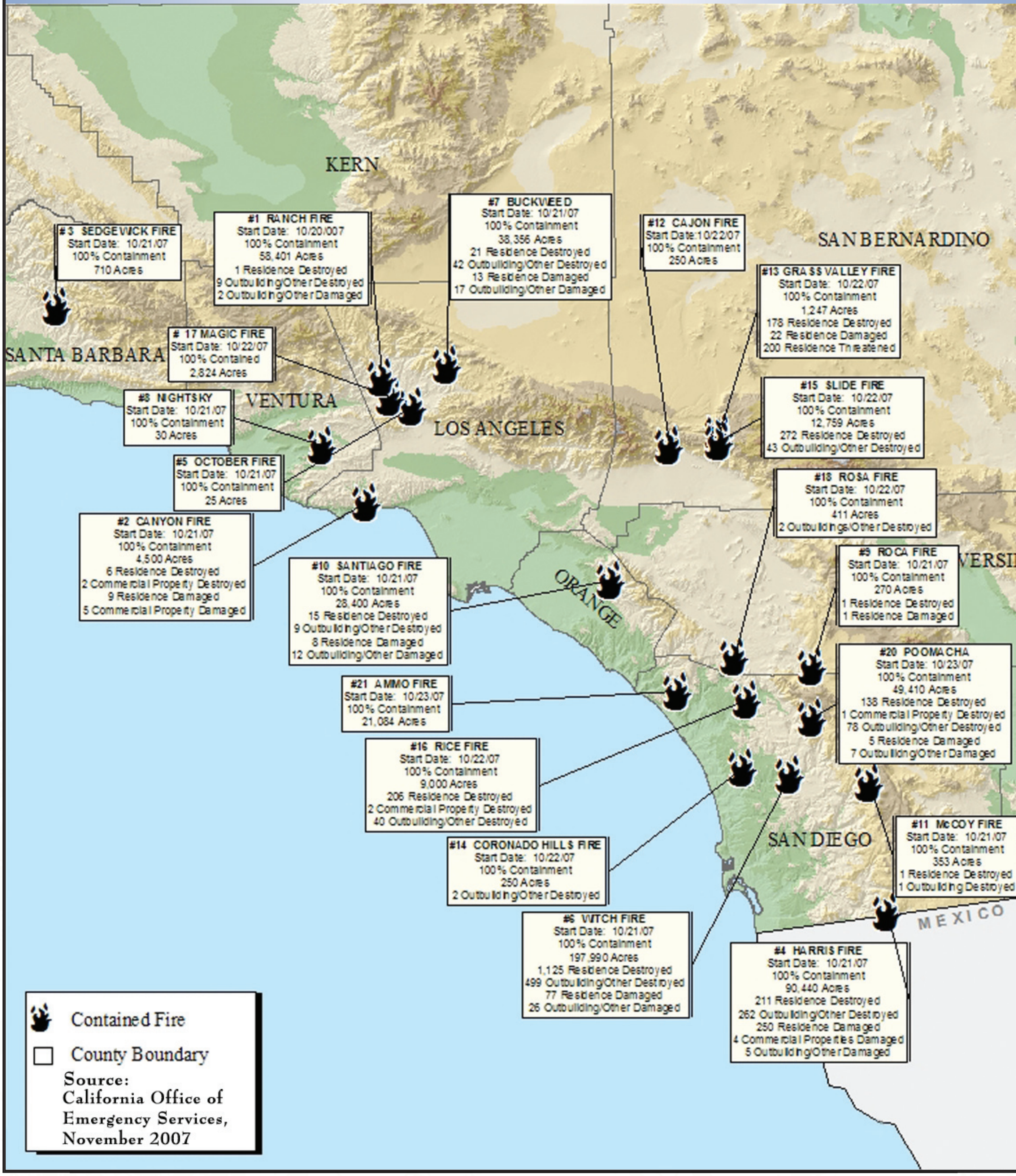


Table 2

ENSO Years, 1985-2006 Classification Based on Average Value of Southern Oscillation Index (SOI) for June-November of Year Indicated

Year	El Niño	La Niña	Neutral	Comments
1985			x	
1986			x	
1987	x			
1988		x		
1989			x	
1990			x	
1991	x			
1992	x			
1993	x			
1994	x			
1995			x	
1996			x	
1997	x			
1998		x		
1999			x	Ocean temperatures reflective of La Niña
2000		x		
2001			x	
2002	x			
2003			x	
2004	x			
2005			x	
2006	x			

1. Data source: Western Regional Climate Center
2. See discussion in text regarding classification of ENSO events by SOI or by sea surface temperatures.
3. Although the classification is shown on an annual basis, ENSO events may span multiple years.

Table 3

Unregulated Inflow to Lake Powell, Recent Drought Period (percent of 30-year average)

Water Year	Percent
2000	62
2001	59
2002	25
2003	51
2004	49
2005	105
2006	71
2007	69

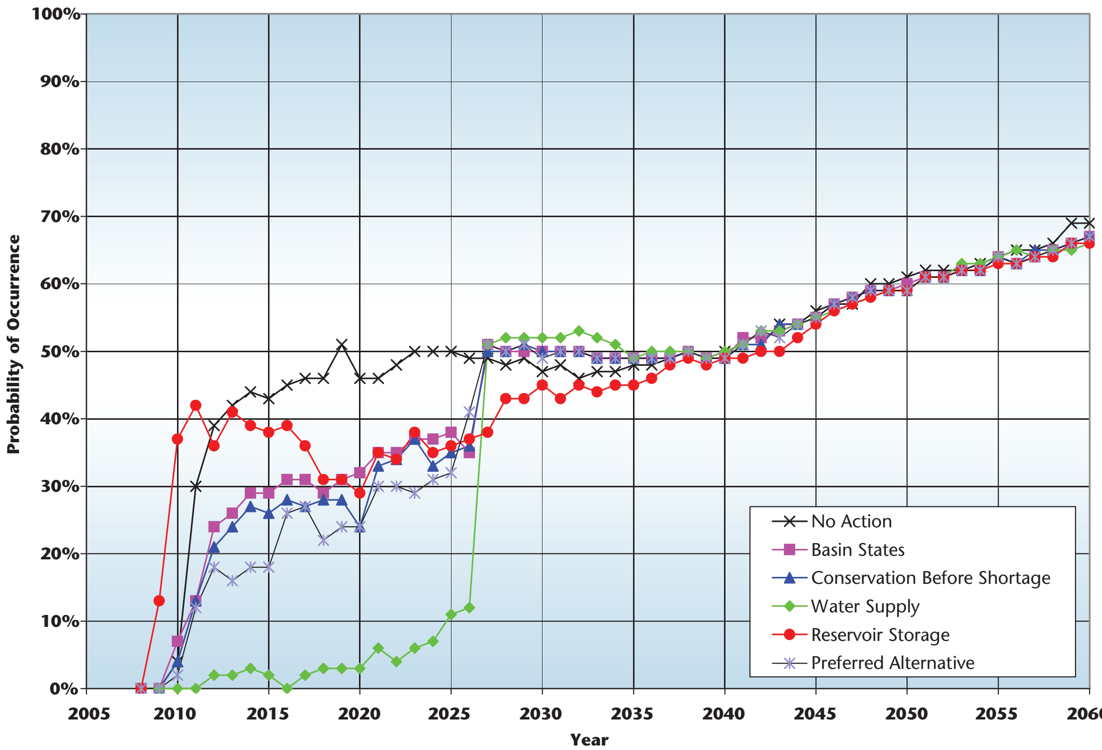
Drought in the Colorado River Basin

The eight-year period from water years 2000 through 2007 was a period of unprecedented dryness in the Basin when compared to the roughly 100-year historical period of measured hydrology. This drought period is also the first during which the Lower Basin was using its full interstate apportionment of 7.5 Million Acre-Feet (MAF) annually. Table 3 shows unregulated inflow into Lake Powell (used as an indicator of water supply conditions) during this time period.

The Colorado River system is distinguished from many other river basins in the West by its reservoir storage capacity – equivalent to about four times the river's average annual flow of 15 MAF. Users of river water in the United States and Mexico did not experience reduced deliveries during the ongoing drought thanks to this storage capacity. Total reservoir system storage in the Basin dropped to as low as 52 percent of capacity in 2004; total system storage at the end of water year 2007 was 54 percent of

Figure 2

Involuntary & Voluntary Lower Basin Shortages Comparison of Action Alternatives to No Action Alternative
Probability of Occurance of any Shortage Volume



Source: USBR 2007 Final Environmental Impact Report

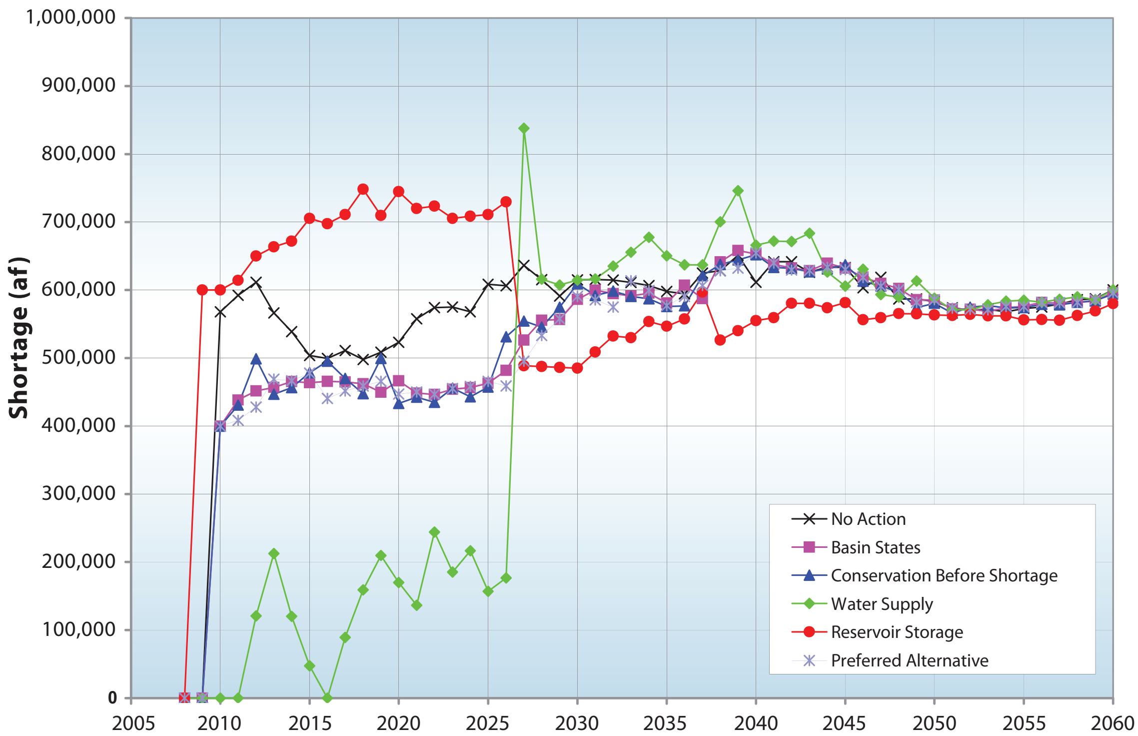
capacity. Although drought conditions have not resulted in shortages of Colorado River water deliveries to date, the prospect of shortages becomes increasingly likely in the future. The 1922 Colorado River Compact was negotiated based the wettest period of the measured hydrologic record; its negotiators believed the river's average annual natural flow at Lees Ferry to be 16.4 MAF. The interstate apportionments in the Compact, together with a subsequent apportionment for Mexico in the 1944 Water Treaty, total 16.5 MAF, while the calculated average annual natural flow at Lees Ferry based on data from 1906 through 2005 is just over 15 MAF.

Figures 2 and 3, taken from USBR's final environmental impact statement for Colorado River interim guidelines for Lower Basin shortages and coordinated operations of Lakes Mead and Powell (USBR, 2007) illustrate modeling results for potential shortages under different operational alternatives. Importantly, all alternatives point to the likelihood of future shortages, representing a significant departure from historical conditions under which Colorado River water supplies were highly reliable. (The probability of shortage to California during the interim period covered in the guidelines, however, is low, owing to the relative seniority of water rights in California.)

Southern Nevada Water Authority Landscape Water Conservation Program

The Colorado River provides about 90 percent of the water supply for Las Vegas and surrounding communities. Nevada received the smallest interstate apportionment of river water under the 1922 Compact, 300 TAF of consumptive use annually. Explosive growth in the Las Vegas metropolitan area during the 1990s brought Nevada up to full use of that apportionment. Southern Nevada Water Authority (SNWA) began a new water conservation program in 1999 that would help address growth in service area water use and respond to Colorado River Basin drought. Its Water Smart Landscapes Program provides rebates to customers that replace turf with water-smart landscaping. SNWA presently pays residential customers $1.50 per square foot of lawn removed and replaced with xeriscape, with no limits on square footage. Since program inception in 1999, SNWA has provided more than $90 million in rebates to customers, corresponding to conversion of more than 2,200 acres of lawn.

Figure 3
Involuntary and Voluntary Lower Basin Shortage Comparison of Action Alternatives to No Action Alternative
Average Shortage Volumes



Source: USBR 2007 Final Environmental Impact Report

Additionally, long-term reconstructions of the river's flow based on tree ring data show that the basin has experienced decades-long periods of drought, periods much longer than those experienced in the short period of the historical gaged record. This paleoclimate analysis of Colorado River runoff is discussed in detail in Chapter 3. A 2007 National Research Council (NRC) study on hydroclimate variability in the basin (NRC, 2007a) noted that:

Multicentury, tree-ring based reconstructions of Colorado River flow indicate that extended drought episodes are a recurrent and integral feature of the basin's climate. Moreover, the range of natural variability present in the streamflow reconstructions reveals greater hydrologic variability than that reflected in the gaged record, particularly with regard to drought.

Drought and Dry Conditions in the Early 2000s

Although the six-year 1987-92 drought was California's most recent statewide drought, a significant four-year regional drought was experienced in Southern California from water years 1999 through 2002. Parts of Northern and Central California were also dry during part of this time period, although not nearly as dry as Southern California. Communities such as Los Angeles and San Diego experienced their then-driest years of record during the 2001-02 precipitation season.

Drought – Fast Facts

- California experienced six statewide droughts of three years or more during the 20th century.
- 1977 was the driest year of California's measured hydrologic record, when statewide runoff was only 20% of average.
- California has only about 100 years of measured hydrologic record. Paleoclimate information (such as that provided from tree-ring studies) indicates that California has experienced droughts more severe than those in the historic record during climatologically recent time.
- During the 1987-92 statewide drought, most large urban areas coped with water shortage impacts through voluntary conservation and mandatory rationing at 20% to 30% levels.

Defining Drought

One dry year does not constitute a drought in California, but does serve as a reminder of the need to plan for droughts. California's extensive system of water supply infrastructure – its reservoirs, managed groundwater basins, and inter-regional conveyance facilities – mitigates the effect of short-term dry periods. Defining when drought begins is a function of drought impacts to water users. Hydrologic conditions constituting a drought for water users in one location may not constitute a drought for water users in a different part of the state or with a different water supply. Individual water suppliers may use criteria such as rainfall/runoff, amount of water in storage, decline in groundwater levels, or expected supply from a water wholesaler to define their water supply conditions.

The Department used two primary criteria to evaluate drought conditions during the 1987-92 drought – runoff and reservoir storage, either actual or predicted. A drought threshold was considered to be Sierran runoff for a single year or multiple years in the lowest ten percent of the historical range, and reservoir storage during the same time period at less than 70 percent of average. These were not hard and fast values, but guidelines for identifying drought conditions.

Drought is a gradual phenomenon. Although droughts are sometimes characterized as emergencies, they differ from typical emergency events. Most natural disasters, such as floods or wildfires, occur relatively rapidly and afford little time for preparing for disaster response. Droughts occur slowly, over a multi-year period. There is no universal definition of when a drought begins or ends. Impacts of drought are typically felt first by those most dependent on annual rainfall – ranchers engaged in dryland grazing, rural residents relying on wells in low-yield rock formations, or small water systems lacking a reliable water source. Criteria used to identify statewide drought conditions do not address these localized impacts. Drought impacts increase with the length of a drought, as carry-over supplies in reservoirs are depleted and water levels in ground water basins decline. Hydrologic impacts of drought may be exacerbated by regulatory or administrative requirements that place restrictions on a water purveyor's operations to protect environmental resources or to satisfy the rights of senior water rights holders.

The most visible legacy of the Southern California regional drought was the major wildfires that devastated Southern California in the fall of 2003, causing 24 deaths and destroying some 4,000 homes. The Governor proclaimed states of emergency for Los Angeles, Riverside, San Bernardino, San Diego, and Ventura Counties, and the President subsequently issued declarations of major disaster for those counties. The extreme fire behavior experienced during these events – characterized as the then-worst wildfire sieges in California's history – was attributed to a convergence of extended drought, high fuel loads, and unfavorable weather conditions. The 2004 report of the Governor's Blue Ribbon Fire Commission estimated property losses from the fires at more than $2 billion.

The 2003 wildfires in Southern California were reported to be the then- costliest in U.S. history. Photo Credit: National Aeronautics and Space Administration (NASA) Earth Observatory

Most water users in urbanized Southern California were unaffected by this regional drought. Urban users located within the service area of the region's major wholesaler – the Metropolitan Water District of Southern California (MWD) – generally did not experience cutbacks, thanks to the availability of imported supplies and local groundwater management programs. Tables 4 and 5 provide information on annual allocations of water supplies from California's two largest water projects from the time of the last statewide drought onward. The Sacramento and San Joaquin River Basin water year types immediately preceding Southern California's regional drought were classified as wet, as can be inferred from the calendar year 1998 water allocations, yielding generally good water storage conditions going into the dry period. Figures 4 and 5 show historical values of the Sacramento and San Joaquin River Basin water year types.

drought conditions. Well drilling activity increased noticeably in response to the 1987-92 statewide drought and to the 1999-2002 regional drought; residential wells constituted the majority of the new water supply wells.

Table 4

Central Valley Project Water Supply Allocations – Long-Term Contractors

Year			Percent	Supply				
	North of	Delta		South of	Delta	Friant Class 1	Friant Class 2	East Side
	Agricultural	Urban		Agricultural	Urban			
1998	100	100		100	100	100	10	32
1999	100	95		70	95	100	20	39
2000	100	100		65	90	100	17	58
2001	60	85		49	77	100	5	22
2002	100	100		70	95	100	8	8
2003	100	100		75	100	100	5	6
2004	100	100		70	95	100	8	0
2005	100	100		85	100	100	uncontrolled season	28
2006	100	100		100	100	100	uncontrolled season	100
2007	100	100		50	75	65	0	29

Notes:

1. USBR may adjust allocations as the year progresses, in response to changes in hydrologic conditions. Values shown are the final allocations for the year.
2. In all years shown, Sacramento River water rights contractors, San Joaquin River Exchange contractors, and wildlife refuges received 100 percent allocations.

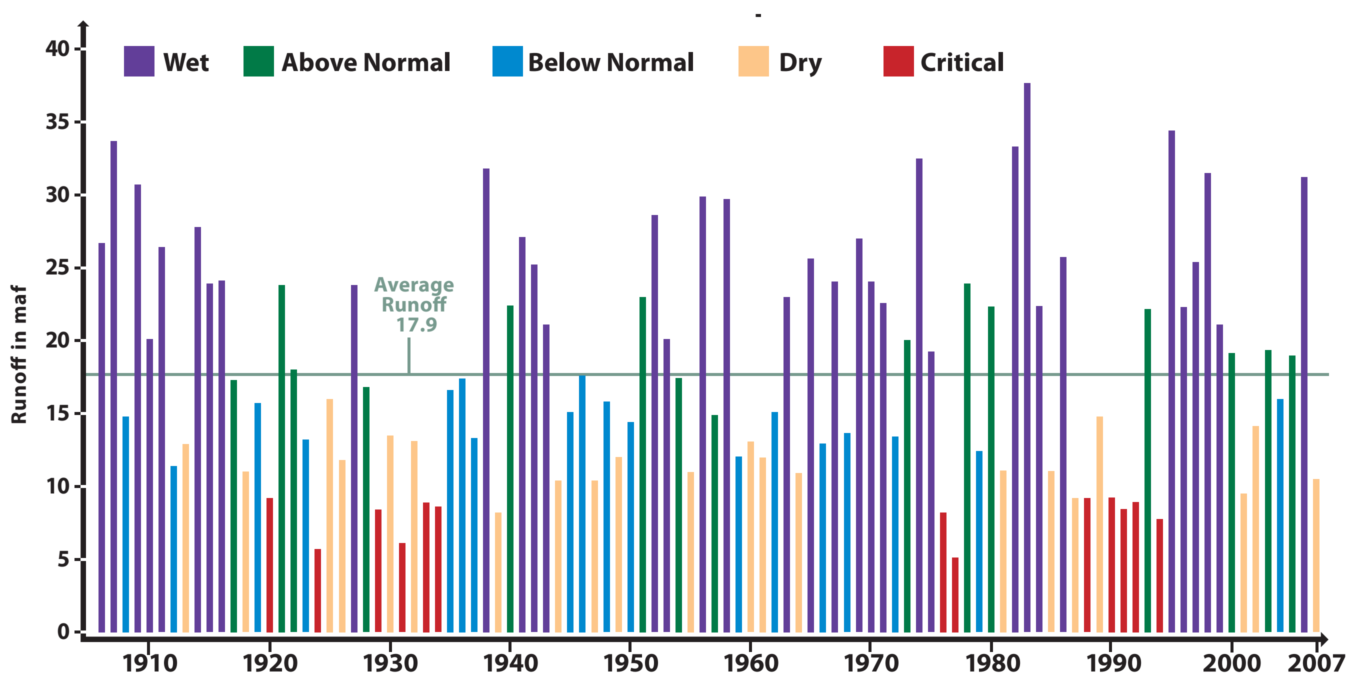
A few small communities outside major urban areas and isolated from regional infrastructure that would have afforded the opportunity for water transfers did experience impacts – especially small communities in interior foothill/mountain areas relying on fractured rock groundwater sources. Affected areas included small communities in the San Jacinto and San Gabriel Mountains such as Pine Cove, Idyllwild, or Big Bear Lake, where local water suppliers took actions such as imposing mandatory water use restrictions, limiting new connections, or hauling water to cope with the absence of rainfall. Throughout inland foothill and mountain areas, owners of private residential wells relying on fractured rock groundwater experienced declining well yields, and sometimes dry wells. Figure 6 shows the total number of well construction/modification reports received annually by the Department, illustrating the impact of

Table 5

State Water Project Allocations

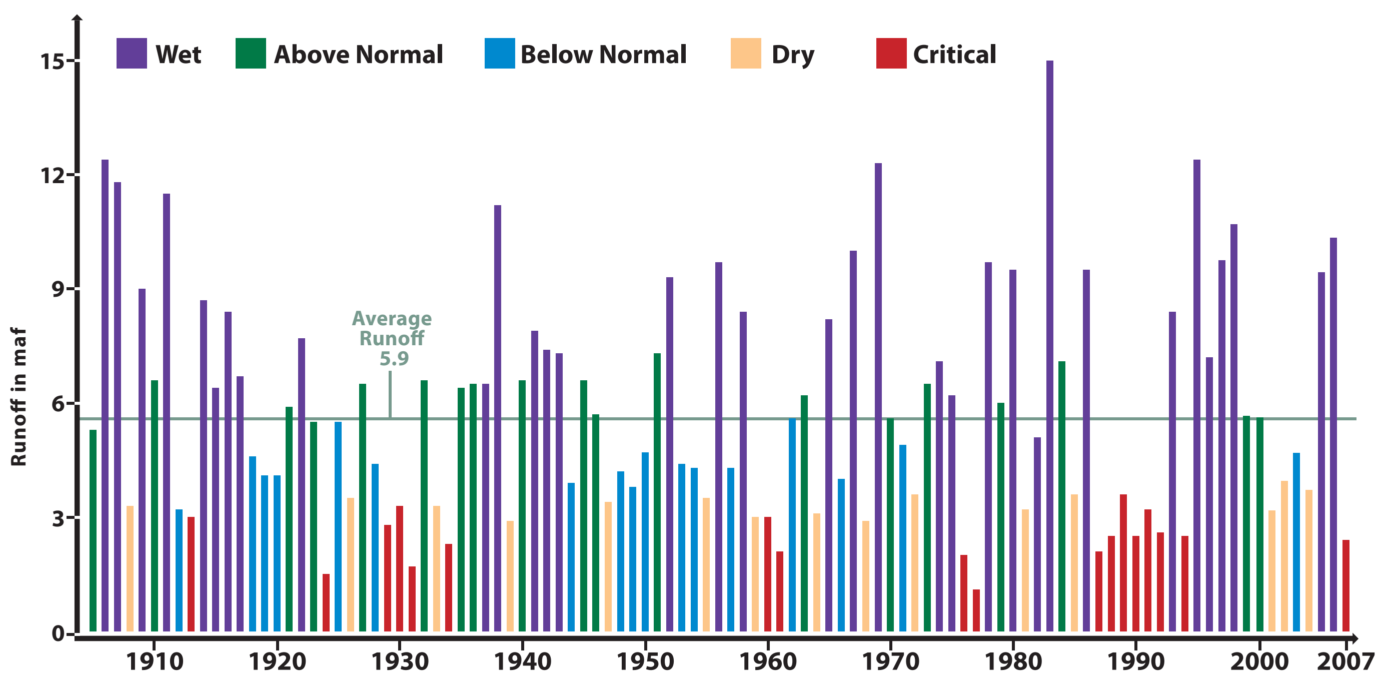
Year	Allocation (% of requested contractual Table A quantity)
1998	100
1999	100
2000	90
2001	39
2002	70
2003	90
2004	65
2005	90
2006	100
2007	60

Figure 4
Sacramento Four Rivers Unimpaired Runoff



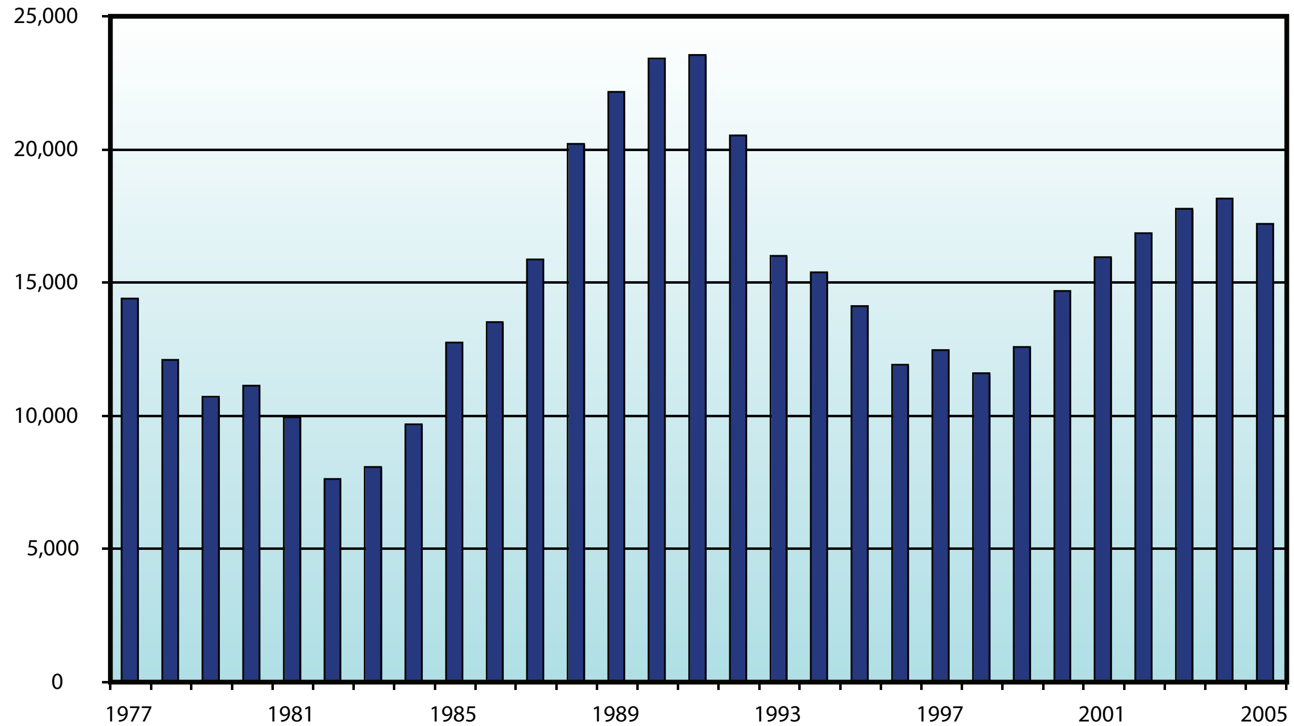
The Sacramento Four Rivers are: *Sacramento River above Bend Bridge, near Red Bluff; Feather River inflow to Oroville; Yuba River at Smartville; American River inflow to Folsom*

Figure 5
San Joaquin Four Rivers Unimpaired Runoff



The San Joaquin Four Rivers are: *Stanislaus River inflow to New Melones, Tuolumne River inflow to New Don Pedro, Merced River inflow to New Exchequer, San Joaquin River inflow to Millerton*

Figure 6
Total Well Driller Reports Filed Annually with Department from 1977 to 2005



Water transfers are one tool for responding to dry conditions. Most of California's major urban areas and agricultural production areas – with the exception of the Salinas Valley – are within reach of a regional conveyance facility or natural waterway that would provide access to water transfers. Multiple urban agencies have established long-term transfer arrangements with agricultural agencies; some of these agreements, like the MWD-Palo Verde Irrigation District 35-year land management program, provide variable quantities of water to the urban partner depending on hydrologic conditions or service area needs. To assist local agencies in responding to water shortages, the Department has operated a dry year water purchasing program to acquire water from willing sellers and make it available to users experiencing shortages. The program, operated in response to interest expressed by users in the early 2000s, made available the following amounts of water:

2001	*138,800 AF*
2002	*22,500 AF*
2003	*11,355 AF*
2004	*535 AF*

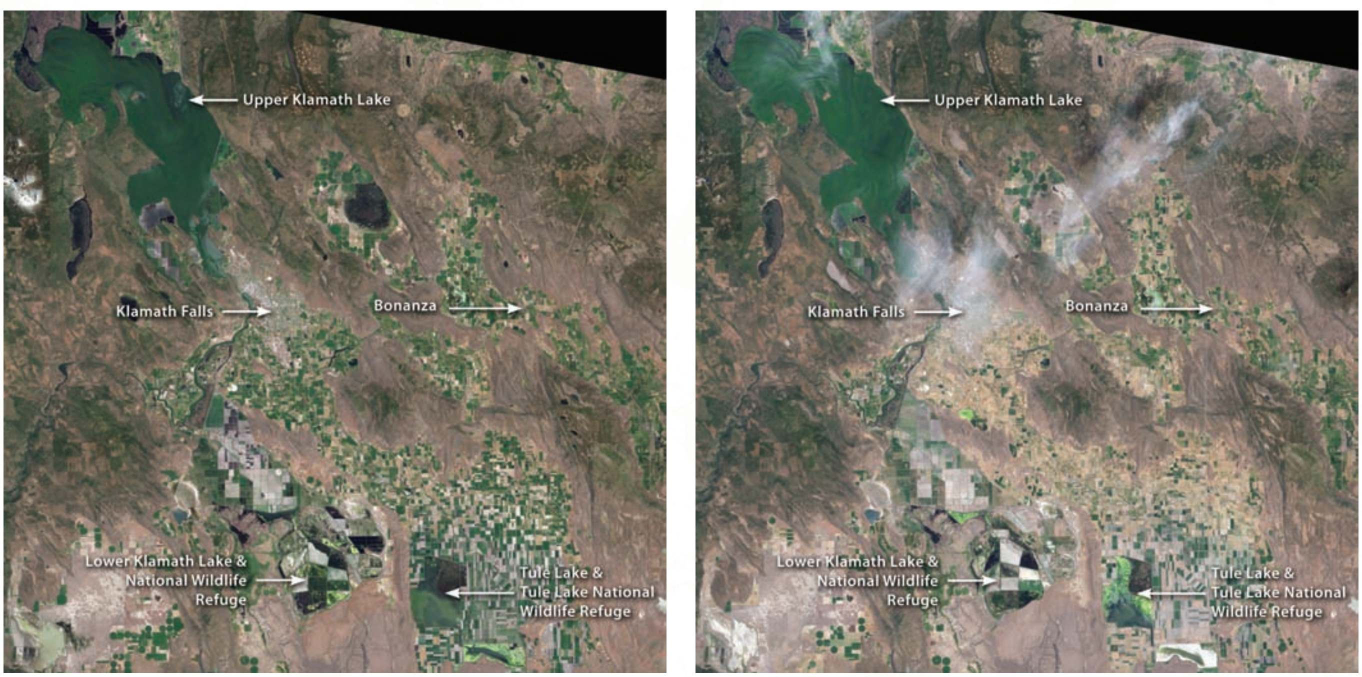
The 2001 Klamath Basin Drought Emergency

USBR's Klamath Project at the California-Oregon border was authorized in 1905, just three years after USBR itself was created. Project construction entailed developing the beds of the former Lower Klamath Lake and Tule Lake for agriculture. About two-thirds of the project's irrigated acreage (in the range of 200,000 acres was under cultivation during the 1990s) is located in Oregon. Irrigation return flows from the project provide water for the adjoining Lower Klamath and Tule Lake National Wildlife Refuges.

The Lost River and shortnose suckers inhabiting Upper Klamath Lake (upstream from the project service area) were listed as endangered pursuant to the ESA in 1988; subsequently, the coho salmon (found in the Klamath River downstream from the project) was listed as threatened in 1997. Spring 2001 biological opinions issued by the U.S. Fish and Wildlife Service for the suckers and by the National Marine Fisheries Service for the salmon called for maintaining Upper Klamath Lake levels to support the suckers while also releasing additional water from the lake to support the salmon. Klamath Basin water year runoff as of April 1st (going into the irrigation season) was 47 percent of average.

USBR announced in April 2001 that no water would be available for lands irrigated from Upper Klamath Lake, or for the Lower Klamath National Wildlife Refuge. Deliveries from the lake in a normal water year would have ranged from 325 to 400 TAF (Congressional Research Service, 2005). Basin water users had historically relied almost entirely on surface water supplies from the project, and did not have alternative sources available. In response, the Governors of California and Oregon issued emergency proclamations for Klamath Basin counties. The California Office of Emergency Services provided $5 million for an emergency project coordinated by the Department to install high production capacity wells to provide limited water supplies for livestock and for irrigating erosion control cover crops. USDA provided emergency assistance through its Farm Service Agency and Natural Resources Conservation Service. Subsequently, greater than expected runoff allowed the Secretary of the Interior to permit release of about 75 TAF from Upper Klamath Lake to provide partial relief for project irrigators. Additional financial assistance was subsequently provided in the 2002 Farm Bill, which earmarked $50 million in USDA's Environmental Quality Incentives Program for conservation practices to help mitigate impacts of shortages.

California's emergency proclamation enabled provision of financial assistance for drilling deep wells to irrigate cover crops used to minimize wind erosion of topsoil from cultivated fields.



These paired Landsat 7 images from NASA's Earth Observatory show the effects of the 2001 reduction in USBR's deliveries to farmers and wildlife refuges in the Klamath Project service area. The image on the left was taken in June 2000, the one on the right in June 2001.

CHAPTER 2

PROGRAMMATIC AND INSTITUTIONAL UPDATES

CHAPTER 2
PROGRAMMATIC AND INSTITUTIONAL UPDATES

This chapter provides updates on selected changed conditions since publication of the Department's 2000 drought report, focusing on actions of an institutional or programmatic nature that have a bearing on drought preparedness or drought response. The chapter begins with updates on two major focal points of imported water supplies – the Sacramento-San Joaquin River Delta and the Colorado River. Next, the unprecedented levels of state financial assistance made available to local water agencies via voter approval of general obligation bonds are described. The chapter concludes with updates on urban water management planning, water transfers, and small water system drought response and preparedness.

The San Francisco Bay-Sacramento/San Joaquin River Delta

The Delta is a hub for delivery of water to urban agencies in the Bay Area and in Southern California, and to agricultural agencies in the San Joaquin Valley. Having certainty in the ability to move water across the Delta is key to local agency water supply reliability in all water year types, and is additionally important in planning for drought response actions such as water transfers. Much has already been written in other documents about the importance of the Delta to California water supplies, the challenges faced in managing the Delta for multiple purposes, and the status of various programs to improve Delta resource management. The following text is intended only to highlight major programmatic actions since the Department's 2000 drought report; detailed treatment of the many Delta-related studies and efforts now underway is beyond the scope of this report.

A Record of Decision (ROD) was signed in 2000 for the multi-agency CALFED Bay-Delta program, marking the program's transition from planning to implementation. The CALFED ROD identified actions that were to be completed during Stage I (the first seven years of the program) and also detailed decisions that were to be made at the end of Stage I, such as decisions about constructing new surface reservoirs. The CALFED program began implementing Stage I actions (e.g. ecosystem restoration activities and water conservation financial assistance) in 2000. Subsequently, the California Bay-Delta Act of 2003 established the California Bay-Delta Authority to serve as CALFED's governance structure.

The CALFED ROD was additionally the impetus for formation of the Governor's Drought Panel, via a commitment that the Governor would convene a panel to develop a contingency plan for reducing near-term impacts of critical water shortages, primarily for agricultural and urban water users. The plan was to build on experience gained with the Department's drought water banks in the 1990s. The Panel's contingency plan focused on actions not covered in the CALFED ROD. Panel recommendations included that the Department implement a critical water shortage reduction marketing program building on the experience of past drought water banks, provide technical assistance for small water systems and homeowners with private wells, expand groundwater data collection and compilation efforts, provide technical and financial assistance for local agency groundwater management and integrated water management planning, and conduct drought-related research and public outreach activities.

As the CALFED program neared the end of its first stage, the Governor's May Budget Revision for Fiscal Year 2005-06 called for an independent review of the program, to be led by the Secretary for Resources. The independent review was completed in 2006 and a new 10-year action plan was developed. Efforts carried out to inform end-of-Stage I decision-making include the Delta Vision Blue Ribbon Task Force report (development of a long-term sustainable vision for the Delta), Delta risk management strategy (analysis of risks and consequences of Delta levee failures), and ongoing surface storage investigations. Also ongoing are scientific studies such as the pelagic organism decline project, intended to improve understanding of the reasons for marked declines in the abundance of pelagic fish species (e.g. Delta smelt, longfin smelt, threadfin shad) in the Bay-Delta. Additional actions are being carried out to develop a Bay-Delta conservation plan as a habitat conservation plan/natural community conservation plan for Endangered Species Act (ESA) and California Endangered Species Act compliance for SWP and CVP diversions from the Delta. Most recently, the Governor outlined a 2008 package of Delta actions that include environmental studies to support the co-equal values of ecosystem restoration and water supply reliability.

In the near-term, limitations on water project exports from the Delta and continuing risks such as substandard levees increase drought vulnerability for agencies relying

There are approximately 1,115 miles of levees protecting 700,000 acres of lowlands in the Sacramento-San Joaquin River Delta. The Delta risk management strategy is assessing major risks to Delta resources from threats such as floods, seepage, subsidence, earthquakes, and climate change.

on Delta exports or seeking to carry out water transfers via the Delta. In the longer-term, a sustainable Delta fix that improves conveyance, restores the ecosystem and increases water storage and conservation is central to improving water supply reliability and drought preparedness for such agencies.

The Colorado River

Execution of the Colorado River Quantification Settlement Agreement (QSA) in 2003 was the culmination of eight years of negotiations over how California would reduce its historical usage of Colorado River water to its basic interstate apportionment of 4.4 million acre-feet per year of consumptive use (plus half of any surplus water, when available). The QSA established an orderly process for California to live within its basic apportionment by quantifying the amounts of water that could be used by the signatory local agencies, providing supplemental detail to the allocation of river water within California set forth in the Seven Party Agreement of 1931. The QSA additionally set aside then-pending litigation over rights to use of river water within California.

California reduced its use of river water to 4.4 MAF in 2003 and has remained at its basic apportionment since that time. California had historically been using about 800 TAF annually in excess of its basic apportionment due to the availability of hydrologic surpluses and water that was apportioned to, but not then needed by, Arizona and Nevada. The availability of this surplus water and unused apportionment during the 1987-92 drought helped buffer the MWD service area from sharply reduced SWP exports during the later years of that drought.

Accompanying the QSA itself were other related agreements, including one providing for a long-term water transfer between Imperial Irrigation District and San Diego County Water Authority. Within California, the 2003 reduction to 4.4 MAF resulted in an immediate reduction to MWD's imported supplies, an impact that is partially offset by the Imperial-San Diego transfer water to be used within the MWD service area. The water transfer began at an initial amount of 10 TAF in 2003; the transfer amount ramps up over time to a plateau of 200 TAF annually in 2023.

The QSA negotiations encompassed use of surplus water as provided for in a 2001 Department of the Interior ROD for interim surplus guidelines. Pursuant to these guidelines, MWD (together with SNWA) would be able to receive special surplus water if reservoir conditions permitted USBR to declare a "domestic surplus" or partial domestic surplus". Subsequent to QSA execution, USBR began a National Environmental Policy Act process for development of interim guidelines for shortage conditions, representing the first-ever guidance on managing the reservoir system under shortage (drought) conditions. The seven Colorado River Basin States began parallel negotiations on shortage management and reservoir system reoperation, ultimately reaching agreement on an approach for more efficient reservoir operations that they recommended to USBR.

In December 2007, the Secretary of the Interior signed a ROD for interim guidelines for Lower Colorado River Basin shortages and coordinated operations of Lakes Mead and Powell through 2026. Subjects covered in the ROD include modification and extension of the pre-existing surplus guidelines, establishment of new shortage guidelines, better coordination of operations of Lakes Mead and Powell, and the ability to store intentionally created surplus (ICS) water in Lake Mead. Pursuant to conditions specified in the ROD, the Lower Basin States may store up to 2.1 MAF of ICS in Lake Mead (1.5 MAF for California and 300 TAF each for Arizona and Nevada); an additional amount of 2.1 MAF is authorized but presently unallocated. Access to storage capacity in Lake Mead, when available, is an important drought preparedness tool for Colorado River water contractors. As indicated in Chapter 1, the Lower Basin is facing a future in which shortages become relatively commonplace. California, however, has a low probability of experiencing shortages during the guidelines' interim period, due to the relative seniority of the involved water rights.

Low reservoir levels at Lake Mead reflect persistent drought in the Colorado River Basin.

State Financial Assistance to Local Agencies

Subsequent to their approval of the landmark Proposition 204 (the Safe, Clean, Reliable Water Supply Act of 1996), voters have continued to support state general obligation bond acts that, among other things, provide funding for water supply infrastructure improvements. These acts include the $1.97 billion Proposition 13 (the Safe Drinking Water, Clean Water, Watershed Protection, and Flood Protection Act) in 2000, the $3.44 billion Proposition 50 (the Water Security, Clean Drinking Water, Coastal and Beach Protection Act of 2002), and the $5.4 billion Proposition 84 (the Safe Drinking Water, Water Quality and Supply, Flood Control, River and Coastal Protection Bond Act of 2006). These bond measures have provided unprecedented levels of grants to local agencies for activities that should improve their water supply reliability and drought preparedness, including groundwater management and storage, desalination, and water conservation. Examples of awarded grants are provided in the appendix.

Beginning with Proposition 50 (Water Code Sections 79500 et seq.) and continuing in Proposition 84, (Public Resources Code Sections 75001 et seq.) emphasis is being placed on the concept of integrated regional water management. The Department's 2005 California Water Plan Update (DWR, 2005) recommended promoting integrated regional water management to "ensure sustainable water uses, reliable water supplies, better water quality, environmental stewardship, efficient urban development, protection of agriculture, and a strong economy". Proposed elements of that approach were defined as fostering regional partnerships, developing and implementing integrated regional water management plans, and diversifying regional water portfolios. Proposition 84 authorized the appropriation of one billion dollars to the Department for fostering integrated regional water management. Grants to local agencies pursuant to this provision are conditioned on the agencies' implementation of integrated regional water plans or their functional equivalents, with the statute further establishing an allocation of funds by geographic area. Figure 7 shows the distribution of the regionally allocated funding.

PROPOSITION 84 (Public Resources Code Sections 75001 et seq.)
INTEGRATED REGIONAL WATER MANAGEMENT PLANNING

The text of the Proposition 84 provisions related to integrated regional water management planning is provided below.

75026. (a) The sum of one billion dollars ($1,000,000,000) shall be available to the department for grants for projects that assist local public agencies to meet the long term water needs of the state including the delivery of safe drinking water and the protection of water quality and the environment. Eligible projects must implement integrated regional water management plans that meet the requirements of this section. Integrated regional water management plans shall identify and address the major water related objectives and conflicts within the region, consider all of the resource management strategies identified in the California Water Plan, and use an integrated, multi-benefit approach to project selection and design. Plans shall include performance measures and monitoring to document progress toward meeting plan objectives. Projects that may be funded pursuant to this section must be consistent with an adopted integrated regional water management plan or its functional equivalent as defined in the department's Integrated Regional Water Management Guidelines, must provide multiple benefits, and must include one or more of the following project elements:

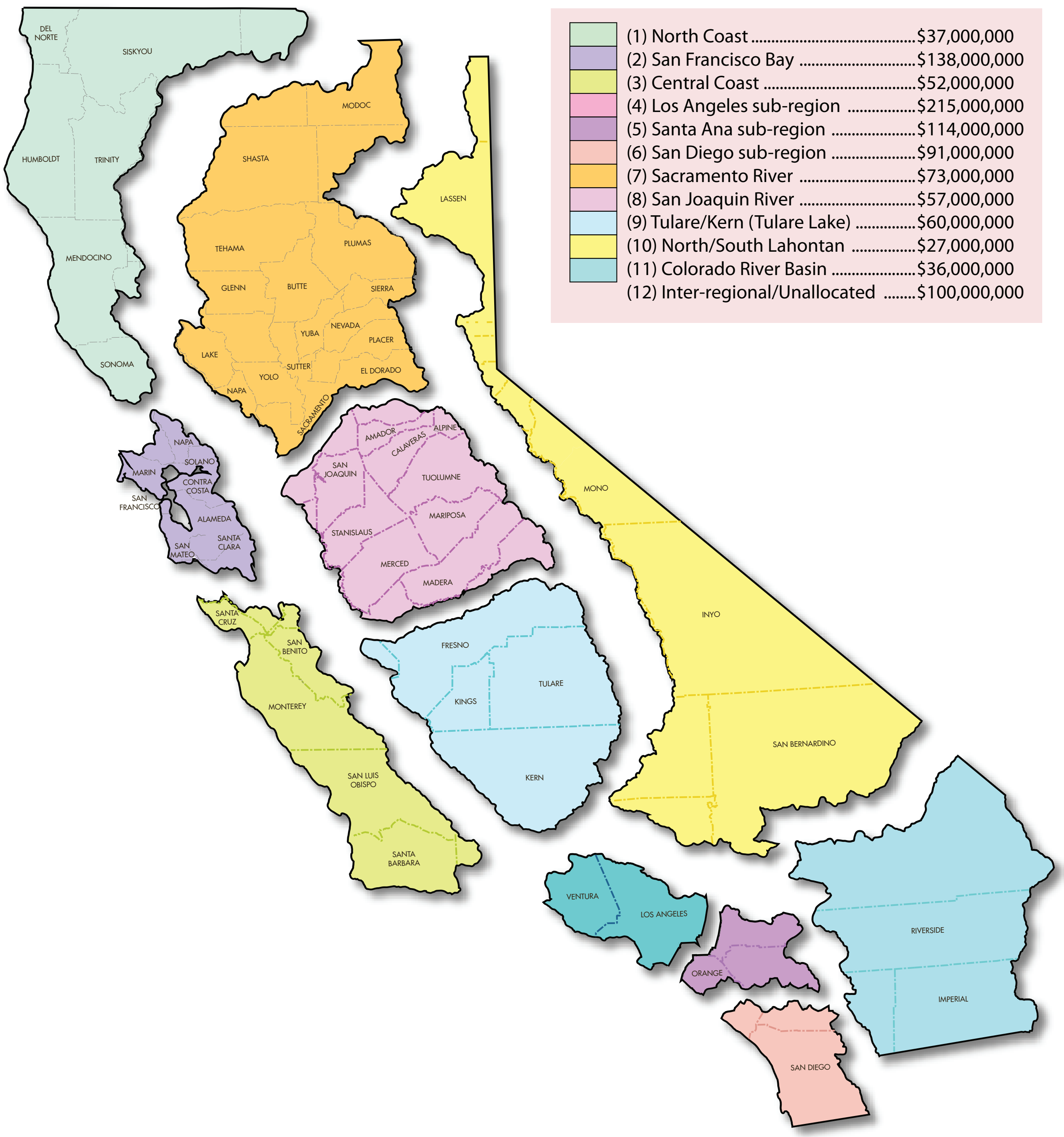
(1) Water supply reliability, water conservation and water use efficiency.
(2) Storm water capture, storage, clean-up, treatment, and management.
(3) Removal of invasive non-native species, the creation and enhancement of wetlands, and the acquisition, protection, and restoration of open space and watershed lands.
(4) Non-point source pollution reduction, management and monitoring.
(5) Groundwater recharge and management projects.
(6) Contaminant and salt removal through reclamation, desalting, and other treatment technologies and conveyance of re claimed water for distribution to users.
(7) Water banking, exchange, reclamation and improvement of water quality.
(8) Planning and implementation of multipurpose flood management programs.
(9) Watershed protection and management.
(10) Drinking water treatment and distribution.
(11) Ecosystem and fisheries restoration and protection.
(b) The Department of Water Resources shall give preference to proposals that satisfy the following criteria:
(1) Proposals that effectively integrate water management programs and projects within a hydrologic region identified in the California Water Plan; the Regional Water Quality Control Board region or subdivision or other region or sub-region specifically identified by the department.
(2) Proposals that effectively integrate water management with land use planning.
(3) Proposals that effectively resolve significant water-related conflicts within or between regions.
(4) Proposals that contribute to the attainment of one or more of the objectives of the CALFED Bay-Delta Program.
(5) Proposals that address statewide priorities.
(6) Proposals that address critical water supply or water quality needs for disadvantaged communities within the region.
(c) Not more than 5% of the funds provided by this section may be used for grants or direct expenditures for the development, updating or improvement of integrated regional water management plans.
(d) The department shall coordinate the provisions of this section with the program provided in Chapter 8 of Division 26.5 of the Water Code and may implement this section using existing Integrated Regional Water Management Guidelines.

75027. (a) The funding provided in Section 75026 shall be allocated to each hydrologic region as identified in the California Water Plan and listed below. For the South Coast Region, the department shall establish three sub-regions that reflect the San Diego county watersheds, the Santa Ana River watershed, and the Los Angeles-Ventura County watersheds respectively, and allocate funds to those sub-regions. The North and South Lahontan regions shall be treated as one region for the purpose of allocating funds, but the department may require separate regional plans. Funds provided in Section 75026 shall be allocated according to the following schedule:

(1) North Coast $37,000,000
(2) San Francisco Bay $138,000,000
(3) Central Coast $52,000,000
(4) Los Angeles sub-region $215,000,000
(5) Santa Ana sub-region $114,000,000
(6) San Diego sub-region $91,000,000
(7) Sacramento River $73,000,000
(8) San Joaquin River $57,000,000
(9) Tulare/Kern (Tulare Lake) $60,000,000
(10) North/South Lahontan $27,000,000
(11) Colorado River Basin $36,000,000
(12) Inter-regional/Unallocated $100,000,000
(b) The interregional and unallocated funds provided in subdivision (a) may be expended directly or granted by the department to address multi-regional needs or issues of statewide significance.

Figure 7
Proposition 84 Regional Funding Distribution

Proposition 84 Integrated Regional Water Management Grant Program Funding Area



Urban Water Management Planning

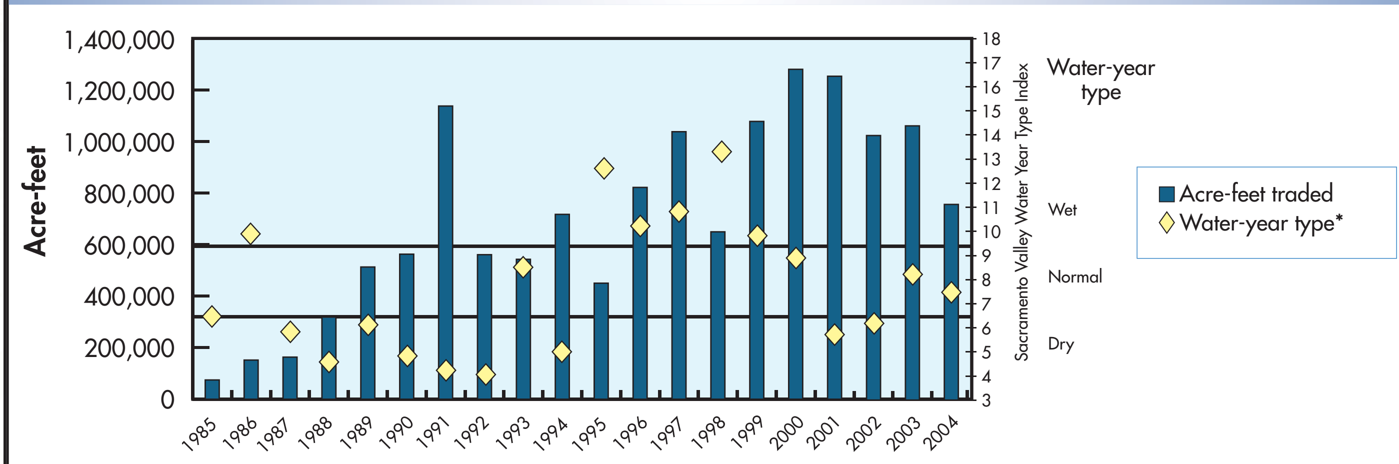
In 2005, the latest updates of Urban Water Management Plans (UWMPs) were due to the Department. Water Code Sections 10601 et seq mandate that urban suppliers prepare UWMPs and update them every five years. The plans are to be submitted to the Department (and to any city or county within which the supplier provides water) in years ending in "0" and "5". The statutory requirement applies to public water systems (both retailers and wholesalers) providing water for municipal purposes to more than 3,000 customers or serving more than 3,000 acre-feet (AF) annually. As part of UWMP preparation, systems must provide a water shortage contingency analysis that addresses how they would respond to supply reductions of up to 50%, and must estimate supplies available to their systems in a single dry year and in multiple dry years. UWMPs must also address systems' responses to catastrophic interruptions of their supplies, such as those caused by earthquakes or power outages. UWMPs can thus serve as larger water systems' planning tool for managing water shortages due to droughts or emergencies. The plans also provide information for water supply assessments required in Water Code Sections 10613 et seq and for written verifications of water supply called for in Water Code Section 66473.7. Eligibility for receiving certain types of State financial assistance is conditioned upon water suppliers having submitted complete UWMPs to the Department. Additionally, legislation enacted in 2007 requires, beginning in 2008, that urban water suppliers implement the demand management measures described in their UWMPs in order to be eligible for specified state financial assistance.

The Department estimated that 413 water suppliers would be required to file plans in the 2000 cycle; 388 plans were actually received. For the 2005 cycle, it was estimated that 459 suppliers were required to file; some 380 plans have been received as of printing of this report. The Department has been reviewing submittals for completeness, and has been following up with suppliers whose plans were incomplete as submitted. The Department, in coordination with USBR and with the California Urban Water Conservation Council, held a series of workshops in response to Water Year 2007 dry conditions to encourage water suppliers to complete their UWMPs and to review their water shortage contingency elements.

Water Transfers

Water transfer activity in California was relatively minimal prior to the 1987-92 drought, as shown in Figure 8, adapted from the 2005 California Water Plan Update. (The figure additionally shows the Sacramento Valley water year type index, to provide an indication of annual water supply conditions.) That drought spurred a dramatic increase in transfers, fueled by the Department's acquisition of more than 800 TAF in 1991 for the drought water bank. Agricultural water agencies have been responsible for much of the growth in transfers since then, as San Joaquin Valley growers seek replacement water for managing reductions in CVP south-of-Delta deliveries following passage of the Central Valley Project Improvement Act (CVPIA). Environmental purchases have also increased, most notably for the CVPIA wildlife refuge pro-

Figure 8 – Estimated California Water Transfer Activity



Quantitative data on transfer activity should be regarded as estimates, as not all water transfers require regulatory or other approvals and hence may not be included in a public record. Updated from DWR, 2005.

gram and for the CALFED Environmental Water Account. The majority of California water transfers are single-year spot market transactions that involve the lease, rather than outright sale, of a water right or contractual right. The ability to carry out transfers can be constrained by the ability to convey water across the Delta, which is influenced by hydrologic conditions, regulatory factors, and capacity available in the Department's California Aqueduct or USBR's Delta Mendota Canal.

A pending regulatory uncertainty with respect to carrying out transfers is associated with litigation in federal courts over the role of the Clean Water Act's National Pollutant Discharge Elimination System (NPDES) permit process in water transfers. In South Florida Water Management District (SFWMD) v. Miccosukee Tribe of Indians, 541 U.S. 95 (2004), the U.S. Supreme Court held that the transfer of water from one waterbody to another could require an NPDES permit if the waterbodies differed in quality. A federal District Court ruling in Friends of the Everglades v. SFWMD [Not reported in F. Supp. 2d, 2006 WL 3635465, 64 ERC 1914, S.D. Fla, December 11, 2006 (NO. 02-80309 CIV)] subsequently held that an NPDES permit was required for SFWMD's pumping floodwaters into Lake Okeechobee, a ruling that SFWMD is presently appealing. In New York, the Second Circuit Court of Appeals affirmed New York City's need to obtain an NPDES permit for the conveyance of water from its Catskill Aqueduct system into a local creek (Catskill Mountains Chapter of Trout Unlimited, Inc. v. City of New York, 451 F.3d 77 (2d Cir. 2006)). Meanwhile, the U.S. Environmental Protection Agency (USEPA) published a proposed rule (71 Fed. Reg. 32887) in 2006 that would exclude water transfers from its NPDES permitting system. No action has yet been taken on USEPA's proposed rulemaking, and further litigation is likely to ensue.

With respect to new federal legislation, in Public Law 109-234 the 109th Congress reauthorized the sunsetting Reclamation States Emergency Drought Relief Act of 1991, extending its provisions through 2010. Among other things, the 1991 act authorized USBR to participate in state drought water banks (California's drought water bank), to acquire water to minimize damages due to drought, and to participate in drought contingency planning.

Small Water Systems and Drought Preparedness

The water reliability problems experienced by small systems in Southern California foothill and mountain areas in the early 2000s are a typical outcome of drought. Small water systems have historically experienced the bulk of health and safety impacts during droughts, as well as the majority of water shortage emergencies. The majority of small system drought problems stem from dependence on an unreliable water source, commonly groundwater in fractured rock systems or in small coastal terrace groundwater basins. Most small systems are located outside the state's major metropolitan areas, often in lightly populated rural areas where opportunities for interconnections with another system or water transfers are nonexistent. Historically, particularly at-risk geographic areas have been foothills of the Sierra Nevada and Coast Range and inland Southern California, and the North and Central Coast regions.

With respect to drought preparedness planning, DWR considers a small water system to be one that is not required to prepare a UWMP, based on the amount of water served or number of customers. The majority of California's public water systems are small systems. Only some 400+ systems are large enough to be required to file UWMPs, although these large systems serve the majority of California's population. By number small systems amount to about 95 percent of the State's public water systems, and nearly 90 percent of community water systems. Even though the total population served by small water systems statewide is relatively small, these communities are typically isolated and have limited back-up water supplies. There is no explicit statutory requirement that small systems plan for drought.

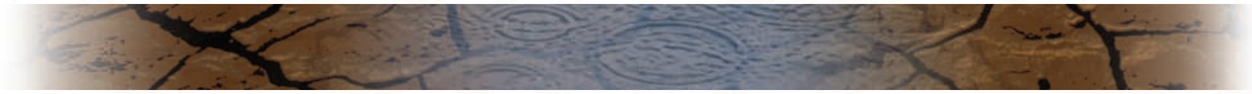
Health and Safety Code Section 116525 requires that all public water systems have permits from the California Department of Public Health (CDPH). For new systems and systems having a change in ownership after January 1, 1998, the water supplier must demonstrate that it has adequate technical, managerial, and financial (TMF) capacity to operate the system in order to obtain a new or amended permit. Demonstration of TMF capacity is also required for public water systems seeking Safe Drinking Water Act state revolving fund financial assistance. The TMF requirements came in response to findings by CDPH that small water systems had difficulty in complying with drinking water standards, and were placing the populations they served at a greater public health risk than that experienced by the general population. One required element of demonstrating TMF capacity is an adequate emergency/disaster response plan, which in effect functions somewhat like the water shortage contingency plan element of a UWMP.

In response to the 2000 recommendations of the Governor's Advisory Drought Planning Panel, the Department initiated a small system technical assistance outreach effort, to help systems improve their drought preparedness. Working through the California Rural Water Association (CRWA), the Department has funded preparation of a small water system database covering approximately 6,500 systems, as well as a small system emergency response/water shortage contingency planning guidebook and website. More than 50 workshops on this subject have been held for small systems, and emergency response plans have been completed for more than 50 small systems. In response to dry conditions in 2007, the Department has worked with CRWA to establish a leak detection technical assistance program for small systems, and has sponsored a conference to focus attention on small system drought problems.

On the federal side, the Rural Water Supply Act of 2006 was approved during the 109th Congress, providing a new source of funding that will be useful in assisting at risk small water systems. The act authorizes USBR to carry out a rural water supply program in the Reclamation Act states, with the program focused on conducting appraisal investigations and feasibility studies of potential projects that would serve communities of 50,000 or less people. Appropriations of $15 million annually are authorized from fiscal years 2007 through 2016; the funds may be used only for studies, no construction funding is authorized.

CHAPTER 3

ADVANCES IN CLIMATE AND DROUGHT RESEARCH



CHAPTER 3
ADVANCES IN CLIMATE AND DROUGHT RESEARCH

There have been major advances in climate-related basic science research since preparation of the Department's 2000 drought report and since California's last statewide drought of 1987-91. This chapter covers recent advances in climate and drought research, focusing on articles solicited from climate scientists whose work spans a broad spectrum of research topics. The chapter opens with a brief overview of the context for drought-related climate research, beginning with a discussion of the climate change research which has fostered substantial discovery science and basic understanding of the climate system. The climate scientists' contributed articles follow.

Overview
Climate and Drought-Related Research

Enactment of the U.S. Global Change Research Act of 1990 marked the beginning of significant federal funding allocations specifically targeted for basic science research dealing with climate variability and change. Over time, scientific understanding of climate processes and the ability to model climate at a global scale have been improving, allowing for better assessment of drought risks and preliminary estimation of climate change impacts to California water resources management. In a 2007 report (NRC, 2007) evaluating the progress of the U.S. Climate Change Science Program (CCSP), the National Research Council noted that: *Good progress has been made in documenting the climate changes of the past few decades and in unraveling the anthropogenic influences on the observed climate changes. The period has witnessed improved understanding of many aspects of the climate and related environmental systems….*

Paleoclimate research has been one of the areas funded by CCSP. The understanding of natural climate variability is improving through increased availability of paleoclimate information such as streamflow records reconstructed via tree-ring studies (see sidebar). Recent work for the Colorado River Basin, for example, has shed light on the severity of the Medieval climate anomaly there, as described in one of the following articles. Improved information on natural climate variability coupled with expected anthropogenic impacts aids in assessing water agencies' vulnerability to drought. As described in following articles, natural variability (e.g. drought duration or magnitude) evidenced in paleoclimate sources can far exceed the variability documented in the relatively short measured historical records.

With respect to research on anthropogenic climate change, the 2007 Fourth Assessment of the Intergovernmental Panel on Climate Change (IPCC, 2007) expressed growing scientific certainty as to observations of climate change, attribution of those observations, and predictions of future trends. There have been significant improvements in global climate model capabilities (Figure 9) since preparation of the Department's previous drought report in 2000 – at that time, only IPCC's Second Assessment Report had been completed. Available information has allowed the Department to make a preliminary quantitative estimate of climate change impacts on SWP and CVP deliveries, as described in the Department's report, *Progress on Incorporating Climate Change into Management of California's Water Resources (DWR, 2006).*

California Hydroclimate Reconstructions

Information about tree-ring reconstructions of streamflow and precipitation at sites in California (also including reconstructions for Colorado River inflow into Lake Powell) has been made available by NOAA on its California TreeFlow web site (http://www.ncdc.noaa.gov/paleo/streamflow/ca/index.html). Also shown are the locations of the tree ring chronologies themselves, with links to the background data at the International Tree Ring Data Bank. Tree-ring reconstructions are useful tools for those interested in assessing the severity of droughts prior to the period of the historical gaged record, or for better understanding long-term natural climate variability. USBR's 2007 EIS covering interim guidelines for Lower Colorado River Basin shortages and coordinated operations of Lakes Mead and Powell, for example, used reconstructed Colorado River flow data in its sensitivity analysis of reservoir operations under alternative hydrologic scenarios.

Figure 9 – Evolution of Global Climate Models Over Time

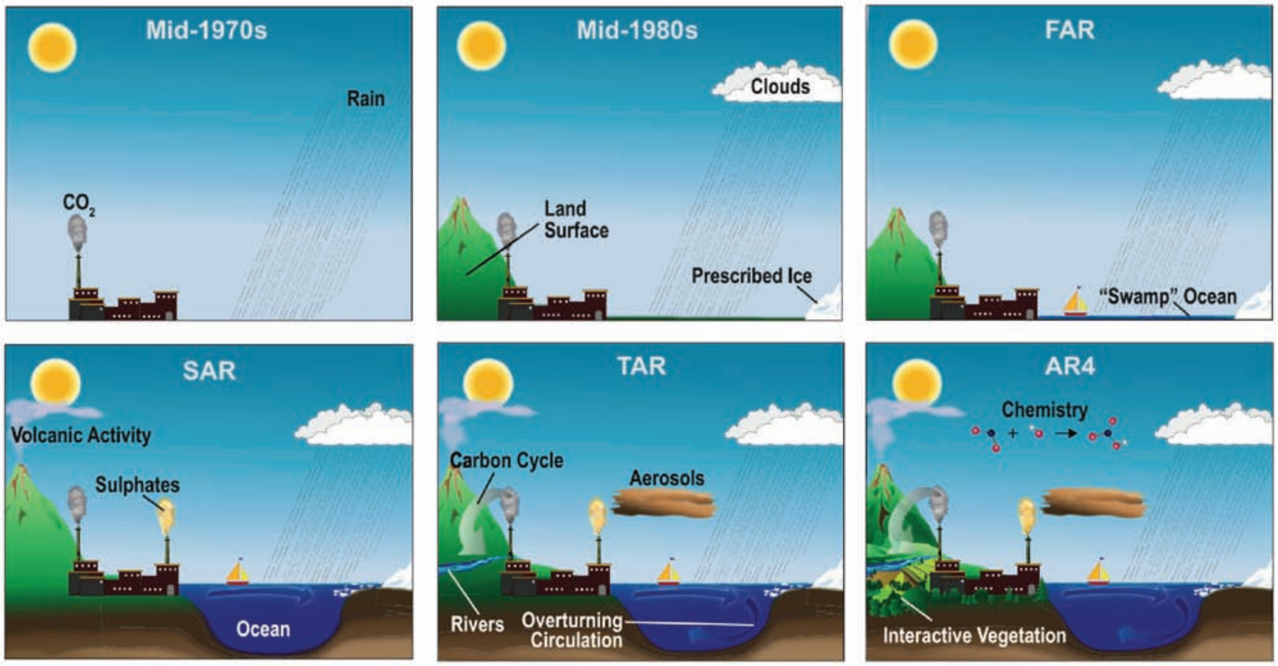


Figure credit: Intergovernmental Panel on Climate Change, Fourth Assessment Report
Legend: FAR= First Assessment Report, SAR= Second Assessment Report, AR4= Fourth Assessment Report

Qualitatively speaking, findings in the IPCC Fourth Assessment are not encouraging with respect to drought:

- *Wet extremes are projected to become more severe in many areas where mean precipitation is expected to increase, and dry extremes are projected to become more severe in areas where mean precipitation is projected to decrease.*
- *All of North America is very likely to warm during this century.…In northern regions, warming is likely to be largest in the winter, and in the southwest USA largest in the summer.*
- *Annual mean precipitation is very likely to increase in Canada and the northeast USA, and likely to decrease in the southwest USA.*
- *Snow season length and snow depth are very likely to decrease in most of North America.*
- *Anthropogenic warming and sea level rise would continue for centuries due to time scales associated with climate processes and feedbacks, even if greenhouse gas concentrations were to be stabilised.*

One finding of the IPCC Fourth Assessment report was that, *Warming of the climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global average sea level.*

Needs for research specific to drought-related topics have been expressed in a variety of sources, including the Department's 2000 drought report and the Western Governors' Association (WGA's) 2004 report on creating a drought early warning system (see NIDIS sidebar). Last year, the Department co-sponsored a workshop on climate change research needs with the Western States Water Council and Western Governors' Association (the proceedings of which are available at http://www.climatechange.water.ca.gov/articles.cfm); some of the climate change research and data needs recommendations made there are also applicable to climate variability and drought. Information gaps/action items identified in the proceedings that are of particular interest with respect to near-term water management include:

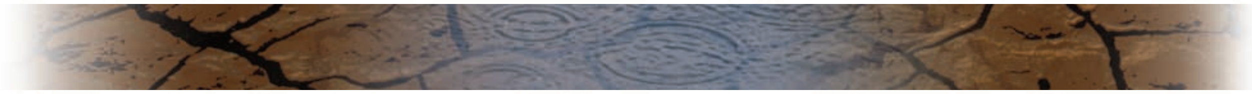
- Improved understanding of ENSO events and storm tracks, especially as they affect winter precipitation.
- Additional paleoclimate studies (streamflow and precipitation reconstructions) to illuminate past hydroclimate variability.
- Filling in gaps in hydrologic monitoring, especially for high elevation snowpack.
- Development of remote sensing applications that would provide early warning of drought impacts.

Contributed Articles

The following articles are intended to illustrate the breadth of recent climate research. First are two articles from the paleoclimate perspective, illustrating how paleodroughts may have affected cultures whose livelihoods were closely tied to site-specific water availability, and quantifying the severity of Colorado River Basin droughts prior to the historical record. The next article takes an operational perspective, considering use of decadal-scale phenomena (e.g. ENSO) to help predict climate variability at time scales useful for water management. The last three articles deal with various aspects of climate change, including climate change impacts in the Colorado River Basin and use of climate models to understand causes of major historical droughts such as the 1930s Dust Bowl drought. Viewpoints expressed in the articles are those of the authors, and do not necessarily represent the views of the Department. The Department thanks all of the authors for their contributions to this report.

The National Integrated Drought Information System

The National Integrated Drought Information System (NIDIS) Act of 2006 charged NOAA with establishing a drought information system that would provide an early warning of drought conditions and coordinate related federal research. A total of $81 million in appropriations was authorized from fiscal years 2007 through 2012. Key components of NIDIS are to include improved integration of data collection and observation programs (e.g. satellite-based observations) and development of new analytical tools for decision support. Improved dissemination of observations and monitoring data should be particularly useful for activities that that depend solely on annual rainfall and are not supported by managed water supplies, such as wildfire management and livestock grazing.



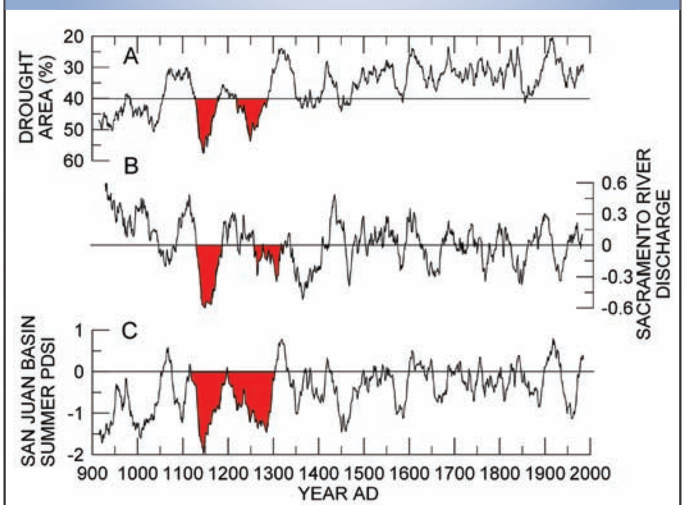
Impact Of Drought On Prehistoric Western Native Americans

Larry Benson PhD, Geochemist, National Research Program, U.S. Geological Survey

The middle-12th and late-13th century droughts

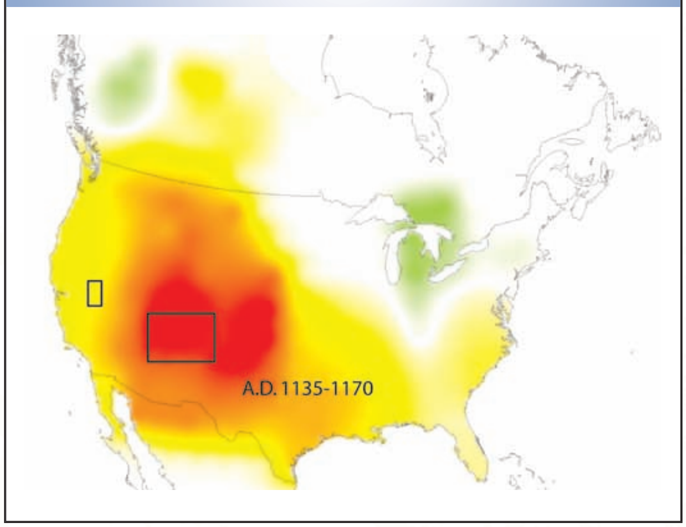
Some droughts that occurred during the so-called Medieval Climate Anomaly (approximately AD 800-1300) appear to have been catalysts for major changes in settlement patterns of two western Native American groups - the Lovelock culture in Nevada's Great Basin and the Anasazi people of the Four Corners area. Both groups' subsistence bases were impacted by diminished water supplies associated with prolonged drought, leading to the dispersal of these Native Americans from their former territories.

Figure 1
Mid-12th and late-13th century droughts
Tree-ring-based climate reconstruction for (A) drought area in the western United States (Cook et al., 2004), (B) normalized Sacramento River discharge (Meko et al., 2001), and (C) summer Palmer Drought Severity Index for the San Juan Basin (Cook et al., 2004).



Tree-ring-based Palmer Drought Severity Index (PDSI) reconstructions by Cook et al. (2004) indicate that over 50% of the western U.S. experienced drought conditions during the middle-12th and late-13th centuries (Fig. 1A, 2). Negative PDSI values indicate dry conditions, whereas positive values indicate wet conditions. This index was specifically designed to evaluate drought impacts on agriculture; PDSI values range from -6 (extreme drought) to +6 (extreme wet). During the middle-12th century drought, there existed a period of 23 consecutive years of negative summer PDSI that represents the single greatest North American megadrought since AD 951 (Cook et al., 2007). The AD 1150-1159 interval was the driest decade during the middle-12th century drought, having a North American average PDSI that was below -1.0.

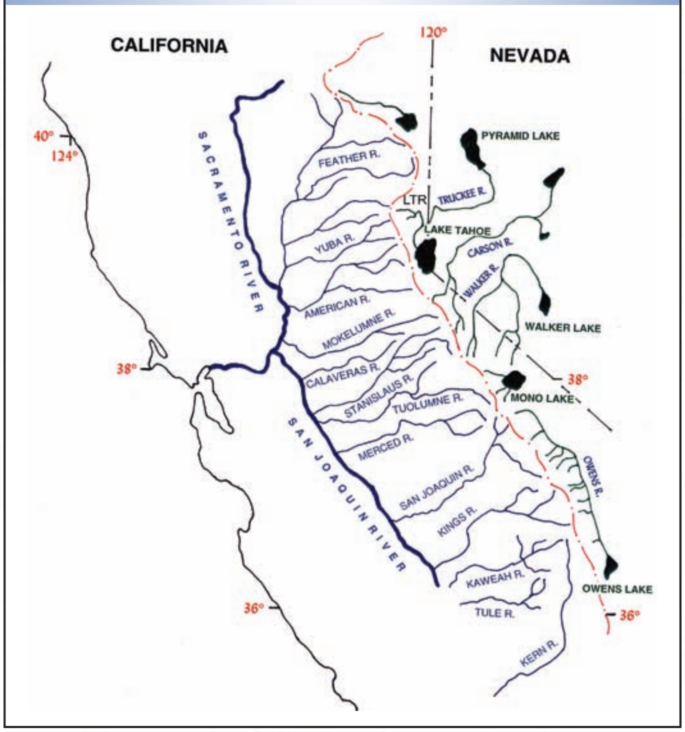
Fig. 2 Mid-12th century drought
Areal extents and intensities of the middle-12th century drought. Yellow indicates a PDSI range of -0.5 to -1, orange -1 to -2, and red -2 to -3. Green indicates a slightly positive PDSI. The large rectangle indicates the Anasazi-occupied Four Corners area; the small rectangle indicates the area occupied by the Lovelock Culture.



Drought in the western Great Basin and the Sierra Nevada

The middle-12th century droughts are evident in the Meko et al. (2001) tree-ring-based reconstruction of Sacramento River discharge (Figs. 1B, 3), in the oxygen-isotope record of Pyramid Lake, Nevada (Figs. 3, 4) (Benson et al., 2002), and in the tree-stump record of Mono Lake, California (Figs. 3, 5) (Stine, 1990, 1994). Annual discharges of rivers that drain both sides of the Sierra Nevada north of 37ºN (about the latitude of Friant Dam on the San Joaquin River) are highly correlated ($R^2 \approx 0.9$) (Benson et al., 2002); thus, if we can estimate the change in hydrologic balance that one surface-water system has experienced, we can transfer the relative degree of change to other surface-water systems in the region. Stine (1998) estimated that discharge to Mono Lake decreased by at least 40% during the middle-12th and late-13th century droughts; therefore, we can estimate the effect of such a dry period on the water balance of western Great Basin lakes and sinks that receive the majority of their inflow from streams draining the Sierra Nevada (Fig. 3).

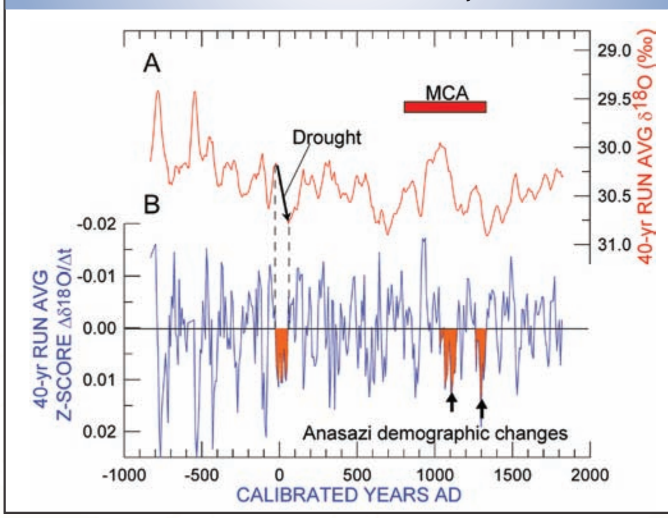
Figure 3
Sierra drainages
Surface-water systems that drain the Sierra Nevada. The Sierran crest in indicated by a red dot-dash line. The Little Truckee River is denote by LTR.



Impact of drought in Nevada's western Great Basin

If the inflow to Lake Tahoe were to decrease by 40%, Lake Tahoe would cease spilling to the Truckee River and, as a consequence, 32% of the input to the mainstream Truckee River would be lost (Benson et al., 2002). In addition, if the Little Truckee drainage (Fig. 3) that provides about 70% of mainstream Truckee discharge would be also reduced by 40%, the mean-annual discharge reaching Pyramid Lake would be decreased by at least 60% (Benson et al., 2002). Such an intense drought would eventually result in a reduction in the surface elevation of Pyramid Lake by 77 m; i.e., Pyramid Lake would go from a situation in which it naturally spilled to the adjacent, and presently dry, Winnemucca Lake basin to a situation in which it was hydrologically closed and relatively shallow (45 m). In 1913, when Pyramid Lake was spilling to the Winnemucca Lake basin, it had a volume of 37.1 km^3 and a total dissolved solids (TDS) concentration of 3920 mg/L (Jones, 1925). If during drought, that volume were reduced to 6.1 km^3 (volume at 45-m level), the TDS concentration of Pyramid Lake would increase to 23,700 mg/L. Under these conditions, Pyramid Lake would resemble present-day Walker Lake; i.e., it would turn over in the summer and winter and the native cutthroat trout fishery would fail. In addition, Winnemucca Lake would desiccate within two decades (It did so historically between 1906 and 1939 as a consequence of the partial diversion of Truckee River water to the Carson Desert) (U.S. Geological Survey, 1960). Thus, wetland-adapted Native Americans, dependent on the Pyramid Lake-Winnemucca Lake complex, would have their subsistence base greatly reduced. In addition, it is highly probable that both the Carson and Humboldt Sinks not only would have been reduced in area, but also would have frequently desiccated by the end of the autumn.

Figure 4
Pyramid Lake Oxygen-18 record of drought
(A) Oxygen-18 (18O) record from a sediment core taken in the center of Pyramid Lake, Nevada. When the volume of water discharged to Pyramid Lake by the Truckee River exceeds the volume lost due to evaporation, the 18O value decreases, and vice versa. (B) The derivative of the normalized (Z-scored) 18O value. The Z score of a value is the value minus the mean of the population divided by the standard deviation of the population. When the derivative is positive, lake level is falling. Droughts are associated with such positive values. MCA refers to the Mediaeval Climatic Anomaly.



The possible impact of drought on the Great Basin Lovelock Culture

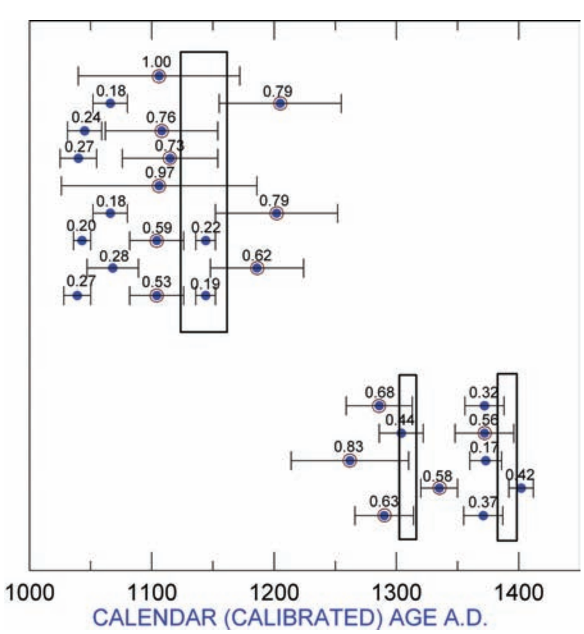
The prehistoric Lovelock Culture was initially defined on the basis of cultural deposits excavated by Loud and Harrington (1929) at Lovelock Cave, Nevada (Fig. 6).
The Lovelock people were hunter-gatherers who lived adjacent to the large terminal lakes/marshes of the western Great Basin, and who relied on the fish and waterfowl from those wetland surface-water systems for much of their food supply. The Lovelock lifestyle is characterized by an intensive lake-sink-marsh adaptation, with the use of caves and rockshelters surrounding lakes, sinks, and marshes, and a suite of distinctive artifact types, including basketry (Grosscup, 1960).

In the following, we use distinctive three-rod-foundation coiled basketry and Lovelock Wickerware basketry as hallmarks of the Lovelock Culture which define their approximate tenure in the western Great Basin.

More than 1000 fragments of Lovelock Wickerware basketry were recovered from Lovelock Cave, Nevada. Originally, the wickerware probably was in the form of conical, burden baskets. Lovelock Wickerware is known only from the Humboldt Sink, Pyramid and Winnemucca lake basins, the Carson Desert, and, possibly, Dixie Valley in western Nevada (Fig. 6).

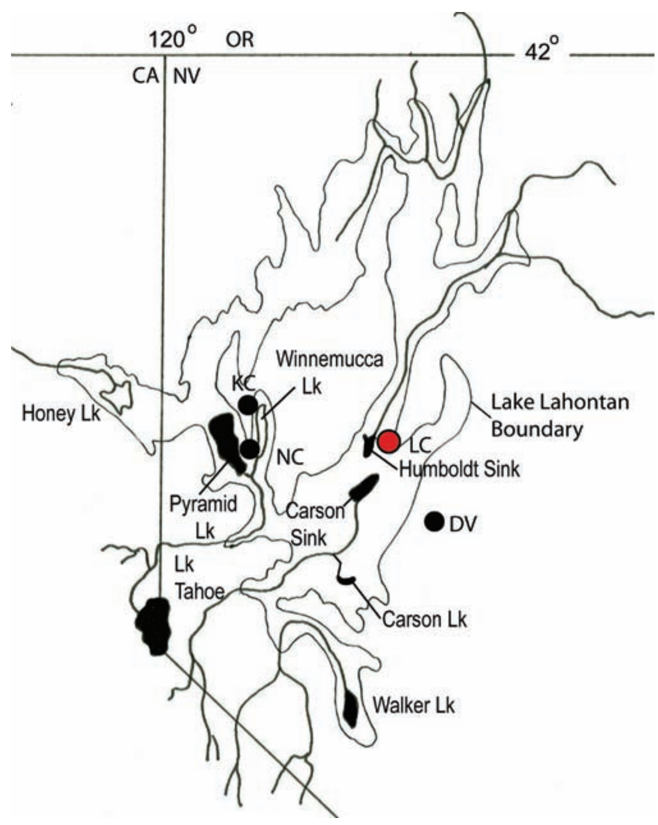
There are relatively few direct dates on Lovelock Wickerware, but existing dates range from 1573±200 BC to AD 1336 ±38 (Tuohy and Hattori, 1996). All radiocarbon dates on Lovelock materials have been calibrated using CALIB 5.01 (Stuiver et al.,1998). The ± value indicates the most probable age range and the number preceding the ± value indicates the midpoint of the range which we assume to be the most probable age of the object. Recently, Benson et al. (2007) dated an additional five Lovelock wickerware samples. All had calibrated ages that fell within the existing age range.

Figure 5
Mono Lake tree stump calibrated ages
Calibrated radiocarbon ages of exposed tree stumps from the Mono Lake basin. Radiocarbon data were taken from Stine (1994). Open rectangles surround times when trees were probably killed by rising lake water. Data indicate drought terminations at about AD 1370, 1300, and 1150. The probability of the 1-sigma age range is given by the number over the symbol. Symbols surrounded by a circle indicate the highest probability range for a single calibration. Vertical axis used to separate data groupings.



Coiled basketry initially appears in western Nevada around 2233±28 B.C. and persists until at least A.D. 1265±14 (Hattori, 1982). The latter date was recently obtained on a coiled, willow water bottle from Lovelock Cave. Therefore, the dates for Lovelock Wickerware and three-rod coiled basketry suggest that the Lovelock people occupied parts of the western Great Basin between about 2200 B.C. and about A.D. 1300. We do not have enough Carbon-14 ages on Lovelock Wickerware and three-rod coiled basketry to determine whether the middle-12th century drought impacted the Lovelock population. However, the disappearance of these textiles during the late-13th century drought suggests that the Lovelock Culture collapsed as a consequence of that drought and that the Lovelock people left the western Great Basin.

Figure 6
Location of some Lovelock rock shelters in the western Great Basin.
The location of Lovelock Cave (LC) is denoted by a solid red circle. Locations of Nicolarsen Cave (NC), Kramer Cave (KC), and Dixie Valley (DV) are denoted by solid black circles.



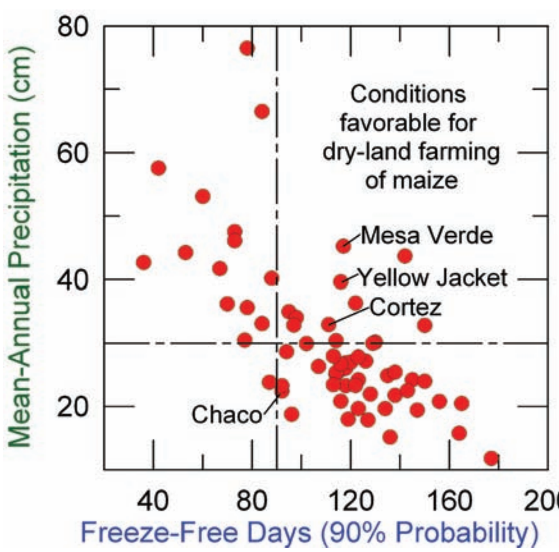
Impact of drought in the Four Corners area

The middle-12th and late-13th century droughts were most intense in the Four Corners area (Fig. 2). The reconstructed summer PDSI for the San Juan Basin (Fig. 1C) indicates that drought impacted the region during most of the time from AD 1130 to 1300.

The link that connects drought and Anasazi migration is maize. Maize was introduced into the southwest ~2240 B.C. and, over time, it became the dietary staple of the Anasazi inhabiting the Four Corners area. In the early historical period, The Hopi and the Zuni attempted to keep a second year's supply of maize in reserve (see e.g., Stevenson, 1904). However, such a reserve would not have been sufficient to last through a multi-year drought.

Maize yields are a function of climate and the properties of the soil in which the maize grows. We do not know the environmental requirements of maize grown by the Anasazi; therefore, we must rely on the requirements of modern forage corn and maize grown by present-day Pueblo people as a proxy. We suggest that Zuni and Hopi agricultural practices are good analogs for Anasazi practices. The Zuni mitochondrial DNA haplogroup distribution is very similar to that of the Anasazi (Carlyle et al., 2000), indicating that the Zuni are descended from one of the Anasazi groups.

Figure 7
San Juan Basin mean annual precipitation vs. freeze-free days
Plot of mean-annual precipitation versus freeze-free days for weather stations in the Four Corners area. Note that about half (49 ± 8%) of the mean-annual precipitation occurs in the warm season (May through September).



Maize is produced in areas that receive 25 centimeters (cm) of annual precipitation or 15 cm of growing season precipitation (Shaw, 1988); however, optimum maize yields occur where growing season precipitation ranges from 40 to 60 cm (Minnis, 1981) and where the freeze-free period exceeds 120 days (Shaw, 1988). At Zuni, May-through-September rainfall averages 15.8 cm and there is a 90% probability that a period of 112 days will be frost-free (Western Regional Climate Center, Desert Research Institute, 2004). Zuni maize cultivars take ~125 days to mature (Muenchrath et al., 2002), and Hopi blue corn requires 115 to 130 frost-free days (Bradfield, 1971).

Freeze-free probabilities and precipitation data exist for 66 sites in the Four Corners area. To determine the best areas for dry-land farming of maize, we assumed that 90 freeze-free days and 30 cm of annual precipitation must be equaled or exceeded. Growing season precipitation averages ~50% of the minimum annual precipitation in the 66 sites. Twelve of the 66 sites have precipitation and freeze-free conditions that permit dry-land farming of maize (Fig. 7), and all 12 sites lie on the periphery of the San Juan Basin (Fig. 8).

Figure 8
San Juan Basin dry-land farming areas
White circles indicate sites in which minimal dry-land farming can occur along the periphery of the San Juan Basin. Orange circles indicate locations of present-day Native Americans (Zuni and Acoma) that remain on the periphery; these people probably arrived at the periphery after the middle-12th or late-13th century droughts.

The impact of drought on the Anasazi

The Anasazi are thought to be the ancestors of present-day Pueblo people who occupy villages in New Mexico and Arizona. The emergence of Anasazi culture is generally associated with the introduction of pottery (at about AD 200 to 300) to an Archaic lifestyle that combined maize agriculture with hunting and gathering.

Over time, the Anasazi became more sedentary as witnessed by evolution in the form and size of their dwellings and villages. Early Anasazi were fairly mobile and tended to move every generation or so, and, in a sense, early pueblo people were nomadic agriculturalists. Between AD 700 and 900, Anasazi architecture took the form of surface pole-and-mud storage rooms constructed adjacent to circular or square-shaped pithouses. By AD 850, stone multistory structures (great houses) were under construction in the San Juan Basin (e.g., Pueblo Bonito; Windes, 2003). Construction of greathouses accelerated between AD 1050 and 1130, and by the end of this period over 207 great houses existed in the Four Corners region (Fig. 9) (Fowler and Stein, 1992; Kantner and Mahoney, 2000).

Thus, the changing architecture of the Anasazi can be interpreted to indicate a culture that evolved to a relatively sedentary agricultural lifestyle in which maize was a dietary staple. Stuart (2000) has estimated that between 10,000 and 20,000 farmsteads populated the Four Corners region by the late-11th century. This is not to say that the Anasazi did not forage in the 11th and 12th centuries but that agriculture dominated their subsistence base.

During the middle-12th century, most of the great houses in the central San Juan Basin were vacated and, during the late-13th century, most of the remaining great houses and many of the smaller villages in the Four Corners area were abandoned (Fig. 9). Great house construction and remodeling in Chaco Canyon ceased at AD 1130 (Vivian and Hilpert, 2002, p. 34). Tree-ring-dated habitation sites also indicate rapid population declines beginning at AD 1130 and 1280 (Fig. 10) (Berry, 1982). Anasazi groups that occupied lands in southwestern Utah, e.g., the Virgin River Anasazi, also abandoned their settlements during the middle-12th-century (Larson and Michaelsen, 1990; Lyneis, 1996).

A comparison of the locations of the 12 weather station sites that permit dry-land farming with locations of great houses occupied after the drought of AD 1150 (Figs. 8 and 9) indicates a measure of congruency, suggesting that the Anasazi may have been forced to leave the relatively cold and dry central San Juan Basin during the drought because that area was no longer able to support dry-land farming. Two of the Native American cultures that stayed in the Four Corners area after the middle-12th and late-13th century droughts (The Zuni and the Acoma) remain on the periphery of the San Juan Basin (Fig. 8).

Some authors have argued that the abandonment of farming was in response to a deterioration of climate (e.g., Hunt, 1953; Rudy, 1953). Lindsay (1986) and Newman (1996) suggested that reduced summer moisture and a shortened growing season (e.g., Salzer, 2000) were the specific causes of agricultural failure, and that the change in climate was due to a shift in the northern boundary of the summer monsoon which today reaches only into southeastern Utah (Mitchell, 1976). This concept is consistent with Petersen's (1994) suggestion that that the expansion of piñon in southwestern Colorado during the 10th and 11th centuries was due to an increase in summer moisture. These studies imply that, prior to AD 1130, the summer monsoon was stronger and its boundary lay north of its present-day position, allowing the Anasazi to expand their territory and increase their population, during a time when maize yields were relatively high.

Fig. 9 Great House abandonment
Great house locations throughout the Four Corners area. Those houses represented by green squares were abandoned before AD 1150 and those represented by yellow triangles were abandoned by AD 1300.

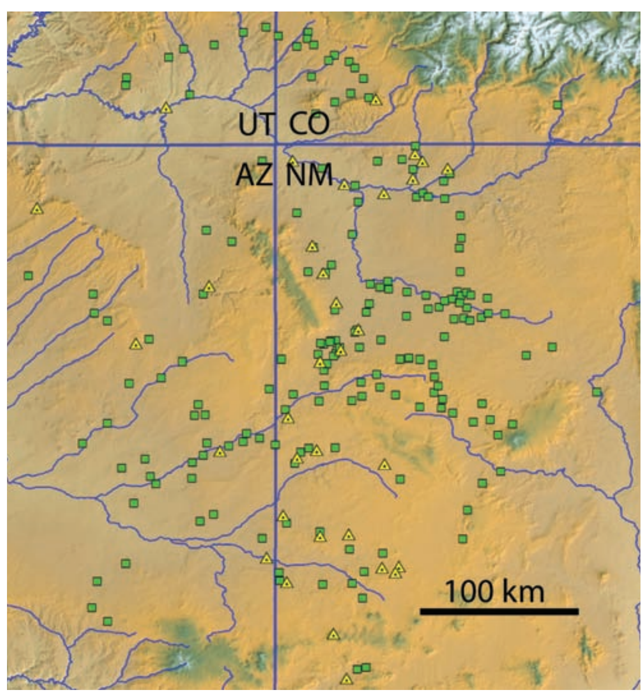
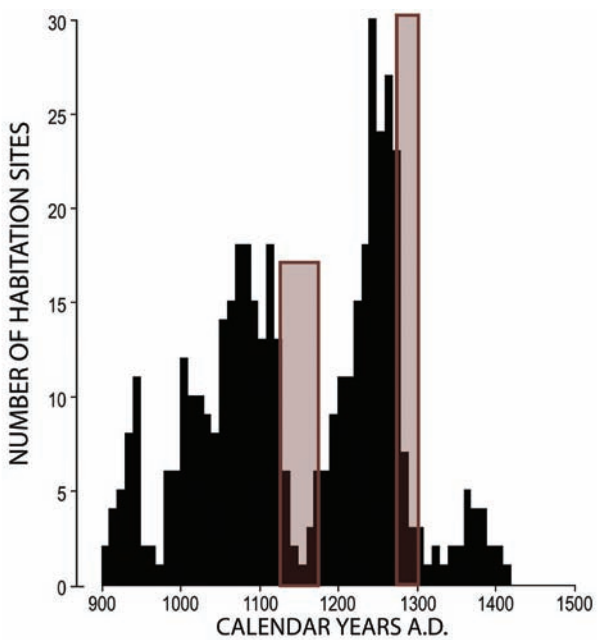


Fig. 10 Four Corners habitation
Number of tree-ring dated habitation sites from the Four Corners area (Berry, 1982). Habitation site number should be considered only a rough nonlinear measure of habitation. Vertical gray-bounded rectangles delineate the middle-12th and late-13th century droughts.



Summary

We have examined evidence of the decline of two prehistoric Native American groups: the Lovelock and the Anasazi Culture. The Lovelock were hunter-gatherers who relied heavily on flora and fauna found in western Great Basin marsh environments. The Anasazi relied on maize horticulture as a principal part of their subsistence base. Thus, both groups relied on resources which were precipitation dependent.

Little or no data exist with respect to Lovelock population dynamics other than the intensive use of caves for caching material culture when compared with preceding and subsequent occupations. However, it would appear that the introduction of horticulture allowed the Anasazi population to increase during times of abundant precipitation. In fact it might be argued that, not unlike existing nation states, these people did not encourage a memory of bad times but allowed their populations, in good times, to expand to the limit of their resource base. We have no data on the response of the Lovelock to the middle-12th-century drought; however, during the subsequent late-13th-century drought, the remnant of the Lovelock culture appears to have abandoned their former homelands.

Between AD 1050 and 1130, accelerated great-house construction occurred across the Four Corners area, including six new great houses in Chaco Canyon. By A.D. 1130, over 207 great houses populated the Four Corners area (Fowler and Stein, 1992). In the middle-12th century, an intense and persistent drought affected much of the contiguous United States. This drought led to massive Anasazi habitation-site declines; e.g., 85 percent of the great houses in the Four Corners area were abandoned, and the late-13th century drought saw the abandonment of the remaining great houses and habitation sites in the Four Corners area.

The droughts of the middle-12th and late-13th centuries probably included both winter and summer drought. This is consistent with the tree-ring study of Fritts et al. (1965) who found that the Great Drought was associated with reduced winter and summer precipitation and elevated summer and autumn temperatures. The middle-12th and late-13th century droughts occurred after population expansions, during a time when people were living at the limit of their environmental and agricultural support systems (Dean et al., 1985; Dean, 1988). Some of the droughts persisted for several years and would have caused all surplus maize to be consumed, thereby forcing the Anasazi to migrate to more agriculturally productive areas.

This concept is reinforced by the work of Burns (1983) who reconstructed maize and bean yields in southwestern Colorado using tree-ring records. Burns (1983) showed that, given a 1.5-year storage capacity, the harshest famines endured by the Anasazi occurred during the middle-12th and late-13th centuries.

The precipitation-dependence of these groups appears to have brought about their demise. In some sense, the two droughts acted as a slow-motion, one-two punch with the first blow putting the cultures on their knees and the second blow ending the fight.

References:

Benson, L. V., Kashgarian, M., Rye, R. O., Lund, S. P., Paillet, F. L., Smoot, J., Kester, C., Mensing, S., Meko, D., Lindstrom, S., 2002. Holocene multidecadal and multicentennial droughts affecting northern California and Nevada. Quaternary Science Reviews 21, 659-682.

Benson, L. V., Berry, M. S., Jolie, E. A., Spangler, J. D., Stahle, D. W., Hattori, E. M., 2007. Possible impacts of early-11th-, middle-12th-, and late-13th-century droughts on western Native Americans and the Mississippian Cahokians. Quaternary Science Reviews 26, 336-350.

Berry M.S., 1982. Time, Space and Transition in Anasazi Prehistory. University of Utah Press, Salt Lake City, UT.

Bradfield, M., 1971. The changing pattern of Hopi agriculture. Royal Anthropological Institute Occasional Paper No. 30, London.

Burns, B. T., 1983. Simulated Anasazi Storage Behavior using Crop Yields Reconstructed from Tree Rings. Ph.D. Dissertation, University of Arizona, Tucson.

Carlyle, S. W., Parr, R. L., Hayes, G., O'Rourke, D. H., 2000. Context of maternal lineages in the greater Southwest. American Journal of Physical Anthropology 113, 85-101.

Cook, E. R., Woodhouse, C. A., Eakin, C. M., Meko, D. M., Stahle, D. W., 2004. Long-term aridity changes in the western United States. Science 306, 1015-1018.

Cook E. R., Seager, R., Cane, M. A., Stahle, D. W., 2007. North American drought: Reconstructions, causes, and consequences. Earth-Science Reviews 81, 93-134.

Dean, J. S., 1988. A model of Anasazi behavioral adaptation. In: Gumerman, G. J. (Ed.), The Anasazi in a Changing Environment. Cambridge University Press, Cambridge, pp. 25-44.

Dean, J. S., Euler, R. C., Gumerman, G. J., Plog, F., Hevly, R. H. , Karlstrom, T. N. V., 1985. Human behavior, demography, and paleoenvironment on the Colorado Plateaus> American Antiquity 50, 537-554.

Fowler, A.P., Stein, J.R., 1992. Anasazi great house in space, time, and paradigm. In: D.E. Doyel (Ed.), Anasazi Regional Organization and the Chaco System. Maxwell Museum of Anthropology, Anthropological Paper No. 5, Albuquerque, pp. 101-122.

Fritts, H. C., Smith, D. G., Stokes, M. A., 1965. The biological model for paleoclimatic interpretation of Mesa Verde tree-ring series. In: Osborne, D. (Ed.), Contributions of the Wetherill Mesa Archaeological Project. Society for American Archaeology Memoir 19, Salt Lake City, pp. 101-121.

Grosscup, G.L., 1960. The Culture History of Lovelock Cave, Nevada. University of California Archaeological Survey Reports No. 52, Berkeley, pp. 1-72.

Hattori, E.M., 1982. The Archaeology of Falcon Hill, Winnemucca Lake, Washoe County, Nevada. Nevada State Museum Anthropological Papers No. 18, Nevada State Museum, Carson City, NV.

Hunt, A.,1953. Archeological survey of the La Sal Mountain area, Utah. University of Utah Archeological Papers No. 14, Salt Lake City.

Jones, J. C., 1925. The Geologic History of Lake Lahontan. Carnegie Institute Publication, 352.

Kantner, J., and N. M. Mahoney (Eds.), 2000. Great house communities across the Chacoan landscape. Anthropo logical Papers of the University of Arizona Number 64. University of Arizona Press, Tucson.

Larson, D.O., Michaelsen, J., 1990. Impacts of climatic variability and population growth on Virgin Branch Anasazi cultural developments. American Antiquity 55, 227-249.

Lindsay, L. W., 1986. Fremont fragmentation. In: Condie, C. J., Fowler, D. D. (Eds.), Anthropology of the Desert West. University of Utah Anthropological Papers No. 110, Salt Lake City, pp. 229-252.

Loud, L.L., Harrington, M.R., 1929. Lovelock Cave. University of California Publications in American Archaeology and Ethnology 25.

Lyneis, M.M., 1996. Pueblo II-Pueblo III change in Southwestern Utah, the Arizona Strip, and Southern Nevada. In: Adler, M.A. (Ed.), The Prehistoric Pueblo World, AD 1150-1350. University of Arizona Press, Tucson, pp. 11-28.

Meko, D. M., Therrell, M.D., Baisan, C. H., Hughes, M. K., 2001. Sacramento River flow reconstructed to A.D. 869 from tree rings. Journal American Water Resources Association 37, 1029-1040.

Minnis, P. E., 1981. Economic and Organizational Responses to Food Stress by Non-Stratified Societies: An Example from Prehistoric New Mexico. Unpublished Ph.D. thesis, Department of Anthropology, University of Michigan, Ann Arbor.

Mitchell, V.L., 1976. The regionalization of climate in the western United States. Journal of Applied Meteorology 15, 920-927.

Muenchrath, D. A., Kuratomi, M., Sandor, J.A., Homburg J. A., 2002. Observational study of maize production systems of Zuni farmers in semiarid New Mexico. Journal of Ethnobiology 22, 1-33.

Newman, D. E., 1996. Pollen and macrofossil analysis. In: Talbot, R. K., Richens, L. D. (Eds.), Steinaker Gap: An Early Fremont Farmstead, Museum of Peoples and Cultures. Occasional Papers No. 2, Brigham Young University, Provo, pp. 123-148.

Petersen, K. L., 1994. A warm and wet Little Climatic Optimum and a cold and dry Little Ice Age in the southern Rocky Mountains, U.S.A. Climatic Change 26, 243-269.

Rudy, J. R., 1953. An archaeological survey of Western Utah. University of Utah Anthropological Papers No. 12, Salt Lake City.

Salzer, M. W., 2000. Temperature variability and the northern Anasazi: Possible implications for regional abandonment. Kiva 65, 295-318.

Shaw, R. H., 1988. Climate requirement. In: Sprague, G. F, Dudley, J. W. (Eds.), Corn and Corn Improvement, Agronomy Monograph No. 18, Madison, pp. 609-638.

Stevenson, M. C., 1904. The Zuni Indians, Their Mythology, Esoteric Fraternities, and Ceremonies. 23rd Annual Report of the Bureau of American Ethnology, Government Printing Office, Washington, D.C.

Stine, S., 1990, Late Holocene fluctuations of Mono Lake, eastern California. Palaeogeography, Palaeoclimatology, Palaeoecology 78, 333-381.

Stine, S., 1994, Extreme and persistent drought in California and Patagonia during Mediaeval time. Nature 369,546-549.

Stine, S., 1998, Medieval Climatic Anomaly. In: Issar, A. S., Brown, (Eds.), Water, Environment and Society in Times of Climatic Change. Kluwer Academic Publishers, The Netherlands, pp. 43-67.

Stuart, D.E., 2000. Anasazi America. University of New Mexico Press, Albuquerque, NM.

Stuiver, M., Reimer, P.J., Braziunas, T.F., 1998. High-precision radiocarbon age calibration for terrestrial and marine samples. Radiocarbon 40, 1127-1151.

Tuohy, D.R., Hattori, E.M., 1996. Lovelock Wickerware in the Lower Truckee River Basin. Journal of California and Great Basin Anthropology 18, 284-296.

U. S. Geological Survey, 1960. Compilation of records of surface water of the United States through September 1950; Part 10, the Great Basin. U. S. Geological Survey Water-Supply Paper 1314, 485 pp.

Vivian, R. G., Hilpert, B., 2002. The Chaco Handbook. The University of Utah Press, Salt Lake City.
Western Regional Climate Center, Desert Research Institute, 2004. http://www.wrcc.dri.edu/

Windes, T.C., 2003. This Old House, construction and abandonment of Pueblo Bonito. In: Neitzel, J.E. (Ed.), Pueblo Bonito, Center of the Chacoan World. Smithsonian Books, Washington, pp. 14-32.

Reconstructions of Colorado River Flow from Tree Rings

Connie A. Woodhouse[1], Jeffrey J. Lukas[2], and David M. Meko[3]

Assessing droughts: The role of paleoclimatology

Drought is a key issue today in California, with drought conditions returning in 2007 after a record wet year in 2006. Notable droughts in California in the past century, as recorded by rainfall and streamflow gages, include the 1930s, late 1980s to early 1990s, and the recent period of drought which started in 1999 and peaked in 2002 (California Department of Water Resources, 2007). The 1930s drought has often been used as a basis for drought planning, but is this an adequate reference point for future planning? Climate change will have impacts on future droughts, but drought planning for the future can be informed by looking into the past, as well as by considering projections from climate models.

Paleoclimatology allows us to assess whether recent droughts are unusual over a long time span that extends many centuries before the start of instrumental climate records. This context is important because the snapshot of climate variation provided by just 100 years of climate records may not adequately represent the full range of climatic variability relevant to water resources management. Paleoclimatic data document climate in times before measurement instruments were available and come from a variety of environmental recorders, such as lake and ocean sediments, ice cores, and tree rings.

Tree rings and how they work

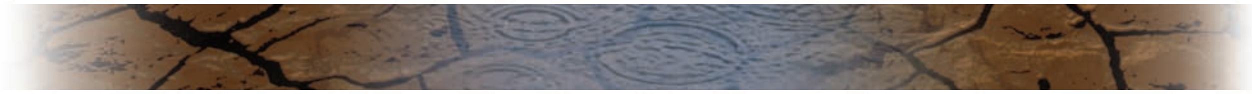
One of the most reliable sources of information on past droughts is tree-ring data. Annual tree rings are faithful recorders of the environmental conditions, mainly climate, that influence tree growth. With careful tree and site selection, the records of annual tree growth reflected in ring widths can be used as a proxy for past climate. In many parts of the western U.S., including California and the Colorado River basin, there is a strong link between the growth of low-elevation tree species (such as ponderosa pine, pinyon pine, western juniper, blue oak, and Douglas-fir and precipitation or streamflow (Schulman 1956, Hidalgo et al. 2001). In the case of streamflow, these conifers, particularly when growing on dry slopes with rocky soils, are sensitive to the same climate conditions that contribute to annual streamflow, primarily winter snowpack, but also precipitation and evapotranspiration (for more detailed discussions on tree growth and streamflow, see Meko et al. 1995) (Figure 1).

When collecting tree-ring samples in the field, we look for the species known to be sensitive to moisture variability (meaning they grow wide rings in wet years and narrow rings in dry years) and sites where these trees are stressed by especially dry conditions. A hand tool called an increment borer— a hollow steel tube with a threaded cutting bit and a handle--is used to extract a core that is about 1/6" in diameter from the tree. Multiple trees are sampled at each site, to enhance the climate information recorded in all of the trees. Back in the laboratory, the cores are mounted, and sanded to a fine finish. They are then "crossdated", by matching the ring-width patterns from tree to tree to assign exact calendar year dates to each ring, and then all of the rings are measured. The ring-width measurements from all of the cores in a site are averaged together to generate a tree-ring "chronology", which is the building block for the reconstructions of past climate.

These reconstructions of past climate are generated from the tree-ring data by calibrating the tree-ring chronologies with a record of seasonal or annual climate (e.g., winter precipitation, water-year streamflow). Using streamflow as an example, we use statistical methods to generate a numerical model in which tree-ring widths estimate annual streamflow, and then use that model to reconstruct streamflow back in time for the length of the tree-ring chronologies. Tree rings do not exactly duplicate the gage record but they can provide a close approximation. For example, about 60%-80% of the variance of annual streamflow is explained by reconstructions in the Upper Colorado, Sacramento, and Salinas River basins (Figure 2).

Figure. 1
Ancient Douglas-fir growing on a steep, rocky slope in the Colorado River basin. Photo by Connie Woodhouse

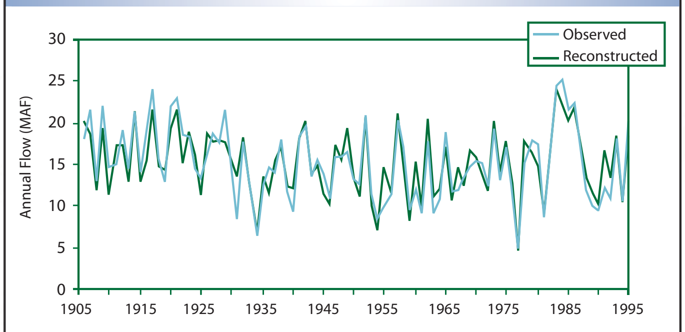
[1] University of Arizona, [2] University of Colorado, [3] University of Arizona



Early investigations and the first reconstruction of Colorado River flow

The first to assess the relationships between tree growth and annual streamflow in the Colorado River basin was University of Arizona scientist Edmund Schulman, in the 1940s. Schulman was motivated, in part, by a practical issue of great concern to the Los Angeles Bureau of Power and Light: the reliability of long-term power generation by the Colorado River (see Schulman 1945, Stockton and Jacoby 1976). He found good potential for reconstructing past streamflow from trees in the Colorado River basin and surrounding areas, and went on to use the information from tree-ring widths to estimate the frequency of drought in the Colorado River basin over past centuries (Webb 1983).

Figure. 2
A comparison of the gage record of water year Colorado River natural flow at Lees Ferry and a reconstruction of flow from tree rings, 1906-1995. The reconstruction accounts for 80% of the variability in the gage record.



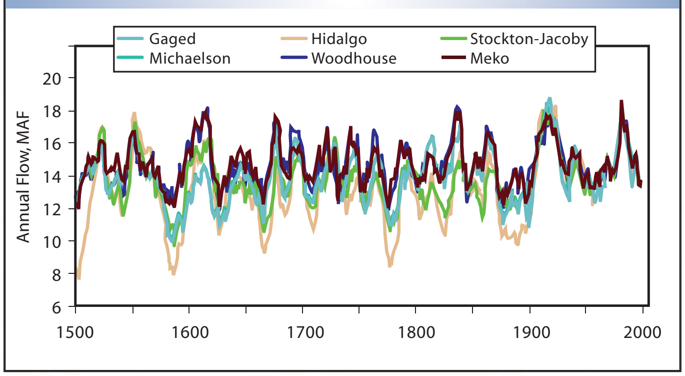
The first "modern" reconstructions for the Colorado River based on statistical calibration of tree-ring data with streamflow records were undertaken by Charles Stockton of the University of Arizona in his PhD dissertation in 1975. His preliminary results were promising, although based on a limited number of tree-ring chronologies. This work was soon updated with new tree-ring collections by Stockton and his colleague Gordon Jacoby from the Lamont-Doherty Earth Observatory (Stockton and Jacoby 1976). They generated three versions of a streamflow reconstruction for the Colorado River at Lees Ferry, Arizona, based on two different gage records, and chose the average of two of these reconstructions based on the common time period 1914 to 1961 to be the most reliable estimate of past flow.

What the Lees Ferry reconstruction showed

The reconstruction of annual flows at Lees Ferry, which is the gage that measures the flow of the entire Upper Colorado River basin, contained several notable features (Figure 3). The highest sustained flows in the record, which extended from 1520 to 1961, occurred in the first two decades of the 1900s, a period that coincides with allocation of Colorado River water resources in the 1922 Colorado River Compact. By contrast, the droughts of the last century appeared to be moderate compared to past centuries, with more severe droughts evident in the tree-ring reconstruction. The worst of these occurred in the late 1500s. This drought event later was used the basis for a set of studies that investigated the hydrologic, social, and economic impacts of a severe, sustained drought in the Colorado River basin (Young, 1995). Other paleoclimatic evidence shows this late 1500s drought impacted much of western North America (Woodhouse and Overpeck, 1998, Stahle et al. 2000).

Several additional Colorado River reconstructions, generated in the years that followed, used similar sets of tree-ring data but different statistical approaches to reconstruct Lees Ferry flow and all showed the same main features (Michaelsen et al. 1990, Hidalgo et al. 2000). More recently, a reconstruction was developed using new tree-ring data which allowed the reconstruction to be updated to 1997 and extended back to 1490, and again this reconstruction showed a very similar pattern of wet and dry years (Woodhouse et al. 2006) (Figure 3). To summarize, although these reconstructions differ in the details related to data and statistical methods, all confirm that the early 1900s period of high flows is unusual in at least the past 400 years, and that drought events have been both more severe and sustained over the past centuries than any in the period of the gage record, which goes back to 1906.

Figure. 3
A comparison of the tree-ring reconstructions that have been generated for the Lees Ferry gage on the Colorado River.



A new 1200-year reconstruction of Colorado River flow

Over the past few years, several researchers have returned to some of the sites where living trees were sampled previously and have collected cross-sections from stumps, logs, and standing dead trees, collectively called "remnant" wood. In the semi-arid climate of the Colorado River basin, wood can remain on the landscape without decomposing for hundreds of years. This wood, from trees that started growing hundreds of years before the trees alive today, can be used to extend the chronologies back in time. The extension is possible because of overlap in time of the remnants and living trees: distinctive ring-width patterns from the outer portion of a remnant can be clearly matched with patterns from the inner portion of the living trees (Figure 4).

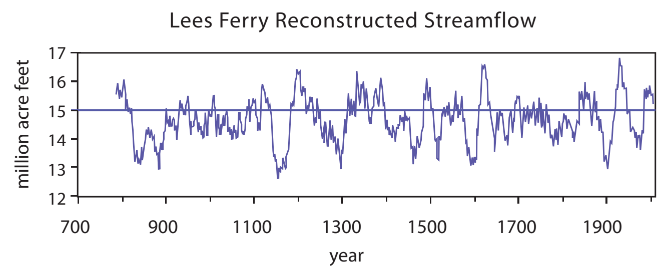
Figure. 4
The remains of an old Douglas-fir tree on Grand Mesa in western Colorado, with the inside date of 927 and outside date of 1724.

The tree-ring chronologies developed from these new collections of remnant wood were used to develop a new reconstruction of Lees Ferry flow back to AD 762, some seven centuries before the start of the previously longest reconstruction (Meko et al. 2007). This is important because it is now possible to examine Colorado River flow during the period known as the Medieval Climate Anomaly (MCA) (e.g., Cook et al. 2004). This period of time was initially recognized by paleoclimatologists as a period of unusual warmth over parts of the world, the North Atlantic and western Europe in particular, from about the 800s to the mid-1400s (Hughes and Diaz 1994). In recent years, scientific evidence has suggested this period was also drier in western North America, with periods of widespread and persistent droughts (e.g. Stine 1994, Hughes and Funkhouser 1998, Bensen et al. 2002, Cook et al. 2004). But how dry were conditions in the Colorado River basin, and what was the nature of droughts during this time period? This new work sheds some light on that question.

Medieval droughts in the Colorado River basin

The reconstruction of Colorado River flow, smoothed with a 25-year running mean, allows an assessment of the variability of flow over decadal time scales (Figure 5).

Figure. 5
Reconstructions of the Colorado River from tree rings, 764-2005, smoothed with a 25-year running average.



Some of the key features of the previous, shorter reconstructions are evident: the early 1900s wet period and the extended drought of the late 1500s century. The wet period is one of just a handful of very persistently wet periods, even in this longer reconstruction back to the 700s. However, the severe drought of the 1500s pales in comparison to a drought in the 1100s. Another period, less severe, but as persistently dry, is evident in the 800s. The lowest reconstructed 25-year running mean occurred in 1130-1154, which was less than 84% of normal (defined as the observed mean annual flow for 1906-2004). By comparison, the lowest 25-year mean of the gage record (1953-1977) was 87% of normal.

The trees document a detailed view of the sequence of annual flows during the 1100s drought. They reveal that the mid-1100s was distinguished by several multi-year low-flow periods within a generally dry period of about six decades (1118-1179). What is remarkable about this period is not extreme low flows for individual years, but an absence of years with flows very much above average. The heart of this dry period is a stretch of 13 consecutive years of below normal flow (1143-1155), with cumulative deficit of 36.5 million acre feet (MAF) , or an average annual deficit of 2.8 MAF (the average annual flow for the gage record is approximately 15 MAF) (Figure 6). By comparison, the longest period of consecutive below- average flow years in the gage record is only five years.

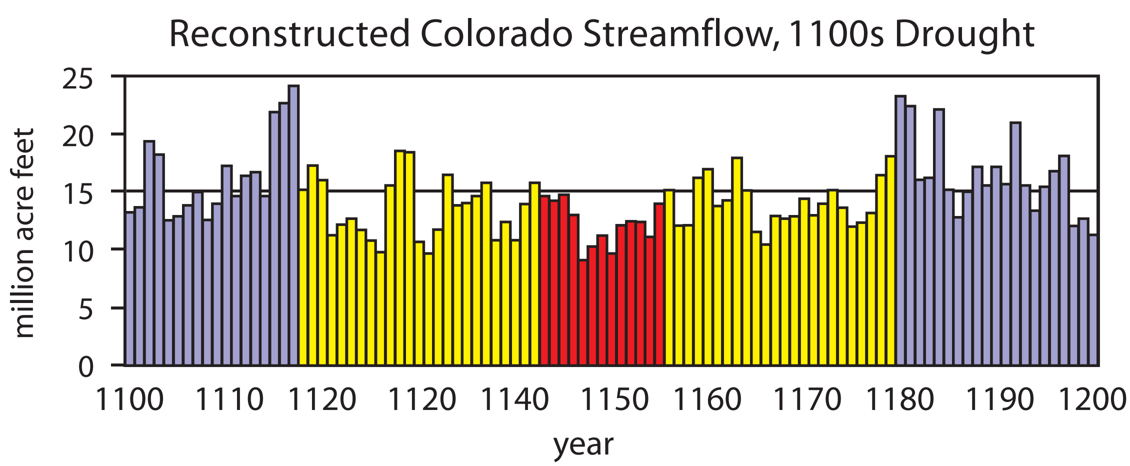
This period of sustained drought in the mid-1100s is documented in other paleoclimatic records in the western U.S. Tree-ring based reconstructions indicate dry conditions in the Sacramento River basin (Meko et al. 2001), the southern Sierra Nevada (Graumlich 1993), the Great Basin (Hughes and Funkhouser 1998) and the Colorado Plateau (Salzer and Kipfmueller 2005), and warm conditions in the Sierra Nevada (Graumlich 1993) and the Colorado Plateau (Salzer and Kipfmueller 2005). Stumps found rooted in the bottom of Mono Lake and other nearby lakes and bogs document periods of drought (and much-reduced water levels) before and after the 1100 drought identified in the Colorado River basin (Stine 1994), and although the dates overlap somewhat, it is not yet clear why the timing of these droughts appears to be different.

Evidence from the past: implications for the future?

Tree-ring based reconstructions are estimates of past climate. Because trees are not perfect recorders of climate and hydrology, there is uncertainty in these estimates. Additional uncertainty may be imparted by the reconstruction process and by errors in the gage data. Nevertheless, these reconstructions provide good evidence that the climate of the past 100 years does not fully represent the range of natural variability that has occurred over the past 500-1200 years. There is no reason to expect that drought events of the magnitude that occurred in the past could not be repeated in the future, as far as we know now. In addition to the extreme droughts, which have obvious impacts on water supplies, these records of the past also show long periods without the high flows critical for refilling reservoirs.

The past climate will not be exactly replicated in the future because of the unprecedented effect of human activities on climate, but the range of natural climate variability is likely to underlie future climate.   Because projections of future climate, particularly precipitation, are uncertain, taking into consideration the broader range of natural variability contained in the reconstructions, along with the impacts of warming that are already evident, may be a prudent course of action in planning for the future.

Figure. 6
Colorado River water year streamflow reconstructed from tree rings, 1100-1200, with the details of the 1118-1179 period of sustained low flows with few years with above average (based on the observed mean annual flow for 1906-2004).



References:

Benson L., Kashgarian M., Rye R., Lund S., Paillet F., Smoot J., Kester C., Mensing S., Meko D. and Lindstrom S. (2002) Holocene multidecadal and multicentennial droughts affecting northern California and Nevada. Quaternary Science Reviews 21, 659-682.

California Department of Water Resources (2007) Drought Preparedness. Background- Droughts in California (http://watersupplyconditions.water.ca.gov/background.cfm)

Cook E. R., Woodhouse C., Eakin C. M., Meko D. M. and Stahle D. W. (2004) Long-term aridity changes in the western United States. Science 306, 1015-1018.

Graumlich L. (1993) A 1000-year record of temperature and precipitation in the Sierra Nevada. Quaternary Research 39, 249-255.

Hidalgo H. G., Piechota T. C. and Dracup, John A. (2000) Alternative principal components regression procedures for dendrohydrologic reconstructions. Water Resources Research 36, 3241-3249.

Hidalgo, H. G., Dracup, J.A., MacDonald, G.M. and King, J.A. (2001) Comparison of tree species to high and low extreme hydroclimatic events. Physical Geography 22, 115–134.

Hughes M. K. and Funkhouser G. (1998) Extremes of moisture availability reconstructed from tree rings for recent millennia in the Great Basin of western North America. In: The impacts of Climate Variability on Forests (ed. M. Beniston and J. L. Innes), pp. 99-107. Springer, New York.

Hughes, M.K. and Diaz, H.F. (1994) Was there a Medieval Warm Period, and if so, when? Climatic Change 26, 109-142.

Meko D. M., Stockton C. W. and Boggess W. R. (1995) The tree-ring record of severe sustained drought. Water Resources Bulletin 31, 789-801.

Meko D. M., Therrell M. D., Baisan C. H. and Hughes M. K. (2001) Sacramento River flow reconstructed to A.D. 869 from tree rings. J. of the American Water Resources Association 37, 1029-1040.

Meko, D.M., C.A. Woodhouse, C.H. Baisan, T. Knight, J.J. Lukas, M.K. Hughes, and M.W. Salzer (2007) Medieval drought in the upper Colorado River basin. Geophysical Research Letters 34m L10705, doi: 10.1029/2007GL029988.

Michaelsen J., Loaiciga H. A., Haston L. and Garver S. (1990). Estimating drought probabilities in California using tree rings. California Department of Water Resources Report B-57105, Department of Geography, University of California, Santa Barbara.

Salzer M. W. and Kipfmueller K. F. (2005) Reconstructed temperature and precipitation on a millennial timescale from tree-rings in the southern Colorado Plateau. Climatic Change 70, 465-487.

Schulman, E. (1956) Dendroclimatic Changes in Semiarid America. University of Arizona Press, Tucson, AZ, 142 p.

Schulman E. (1945) Tree-ring hydrology of the Colorado River Basin. University of Arizona Bulletin XVI(4). University of Arizona, Tucson. 51 p.

Stahle D. W., Cook E. R., Cleaveland M. K., Therrell M. D., Meko D. M., Grissino-Mayer H. D., Watson E. and Luckman B. H. (2000) Tree-ring data document 16th century megadrought over North America. EOS Transactions 81, 121-125.

Stine S. (1994) Extreme and persistent drought in California and Patagonia during mediaeval time. Nature 369, 546-549.

Stockton, C.W. (1975) Long-term streamflow records reconstructed from tree rings. Papers of the Laboratory of Tree-Ring Research 5. University of Arizona Press, Tucson, AZ, pp. 1-111.

Stockton C. W. and Jacoby G. C. (1976) Long-term surface-water supply and streamflow trends in the Upper Colorado River Basin. Lake Powell Research Project Bulletin No. 18. National Science Foundation, 70 p.

Webb, G.E. (1983) Tree Rings and Telescopes: The Scientific Career of A.E. Douglass. University of Arizona Press, Tucson, AZ, 242 p.

Woodhouse, C.A. and Overpeck, J.T. (1998) 2000 years of drought variability in the central United States. Bulletin of the American Meteorological Society 79, 2693-2714.

Woodhouse C. A., Gray S. T. and Meko D. M. (2006) Updated streamflow reconstructions for the Upper Colorado River Basin. Water Resources Research 42, W05415, doi:10.1029/2005WR004455.

Young R. A. (1995) Coping with a severe sustained drought on the Colorado River: introduction and overview, Water Resources Bulletin, 316. 779-788.

Decadal Climate Prediction: Learning from the Oceans

Lisa Goddard [1], Andy Wood [2], Nate Mantua [3], Kathy Jacobs [4]

The weather of the globe is a complex whole, each part of which reacts on every other, and each part of which depends on every other…the remote source of our daily changes, as well as the causes of the greater cycles of change, are still beyond our reach. Although withdrawn from the domain of the unknowable, they remain within that of the unknown.

John Wesley Powell: From the Report on the Lands of the Arid Region of the United States, transmitted to Congress on April 3, 1878.

Climate experts have been aware for some time that climate patterns are driven in large part by ocean temperatures and feedbacks from conditions on the land surface. With climate, we focus on patterns that play out over seasons, years, and decades. Although all of these patterns are likely to be affected by human-caused climate change, understanding the causes of climate variability at each of these time frames is very useful for predictive purposes. The primary source of prediction skill at seasonal to interannual time scales has been associated with the El Niño – Southern Oscillation (ENSO) cycle, a global feature of the ocean and atmospheric circulation that affects climate with a recurrence interval of 2 to 7 years. However, longer-term patterns that are decades in length have been identified in both the Atlantic and the Pacific Oceans. These patterns are associated with long-term droughts, such as the Dust Bowl and 1950s droughts, as well as long term wet periods. The climate signals associated with these decadal oscillations are more obvious in some regions than in others, but in parts of the Southwestern US, relationships between these oscillations and annual precipitation are well established.

In response to drought and increasing demand for water, water managers across the West have expressed an urgent need for more information about future snowpack and water supply conditions. Because water managers make decisions within specific watersheds and regions, their need for water supply predictions is at various geographic scales. Further, there are a range of water management decisions – including reservoir operations, annual water supply decisions, and longer-term infrastructure and water rights acquisition decisions. From a reservoir operations perspective, knowing the likely total precipitation and the potential volume of runoff in the relatively short term – weeks to months – is extremely important from a flood control and water delivery perspective. From an annual water supply perspective, understanding how likely it is that drought conditions will prevail over the months-to-years time frame is critical information.

In contrast, for infrastructure and water rights decisions, understanding the long-term average water supply availability is likely more important than predicting climate variations at operational lead times, though clearly the implications of extreme flood and drought events have to be factored into all of these decisions.

The geographic scale and infrastructure pertaining to a water supply decision turns out to be critical to climate information needs, in part because the amount of water supply storage capacity in individual watersheds can significantly buffer the effects of climate variability. For example, the reservoirs on the Colorado River system, including Lakes Mead and Powell, have so much storage capacity (four times the average annual flow) that the system can deliver at a "normal" level even under severe drought conditions for extended periods of up to a few years. Meanwhile, the reservoir capacity in California is significantly lower relative to the average annual flow of its rivers, in the range of half to a full year. This means that drought vulnerability within the California state reservoir system is higher than it is on the Colorado River system.

Knowing when a drought is likely to end with a transition to wetter conditions is invaluable information for the water managers who operate the Colorado River system as well as those making long term infrastructure, environmental flow and water rights-related decisions in other basins of the West. Understanding what causes the "phase change" from wet to dry periods, and vice-versa, is critically important to predicting when those phase changes may occur. As we face the prospect of losing power production capacity at Lakes Powell and Mead with ongoing drought and dropping water levels behind their dams, millions of dollars hinge on decisions about the volumes of water to release each year. Likewise, as we near the point where concerns are being expressed regarding potential impacts of lower Lake Mead levels on Southern Nevada Water Authority's treatment plant

[1] International Research Institute for Climate Prediction, Columbia University
[2] University of Washington
[3] University of Washington, Climate Impacts Group
[4] Arizona Water Institute

intakes, understanding the probabilities of having a wet versus dry year can help water managers make better decisions about declaring a "shortage" vs "normal" water year on the Lower Colorado.

As California moves towards finding solutions to the Bay-Delta water supply issues and providing reliable water supplies for urban and agricultural water users, a sharper focus on decadal trends will help frame the answers to infrastructure questions such as the need for new storage reservoirs, groundwater recharge facilities, or improved efficiency in water delivery and use. Though we will never have perfect predictive capacity, increasing our understanding of the probabilities of future climate conditions will help water managers make decisions that decrease the vulnerability of water supplies. Increasing the odds of being right about water supply availability also has very significant economic value in power production, agriculture and in minimizing the cost of environmental protection activities. In the climate research community, a growing interest in understanding the mechanisms that -govern decadal-scale variations in the circulation of the ocean and atmosphere may lead to enhanced predictive capacity at this time scale.

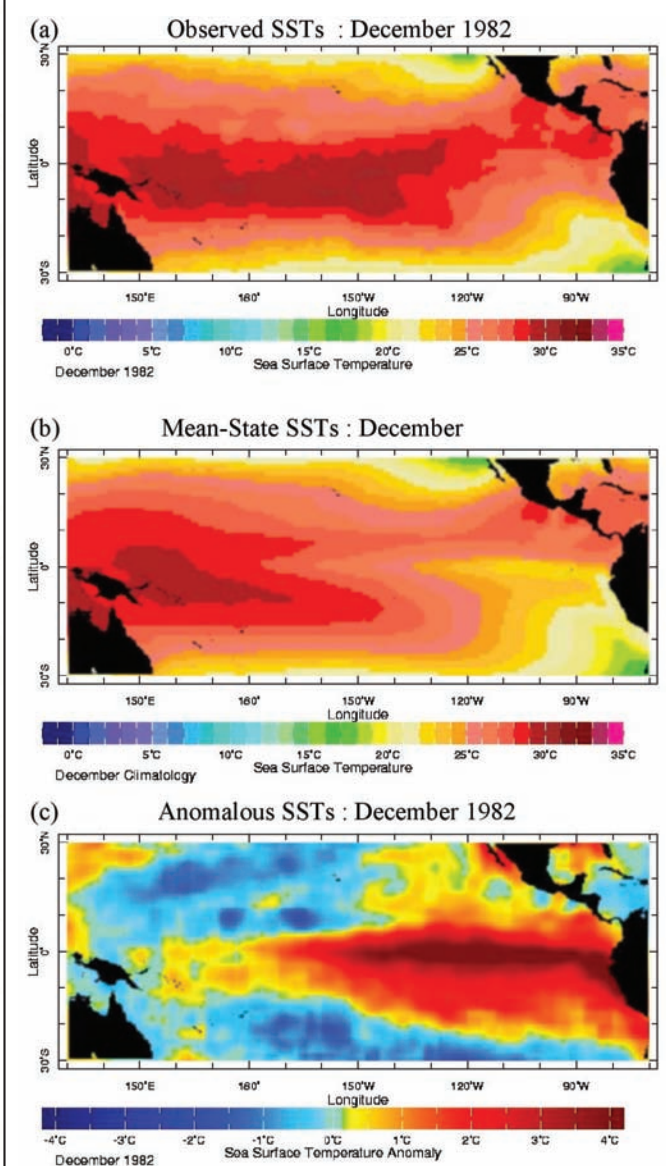
In the following sections we discuss the main ocean-atmosphere teleconnections thought to give rise to hydroclimatic variability on interannual to decadal and longer time scales, their relevance to California climate and water resources, and the implications for research investment priorities from scientific and applications oriented institutions.

The Ocean-Climate Connection

The potentially predictable part of climate variations arises from changes in heat and moisture at the earth's surface or changes in the balance of incoming and outgoing energy due to changing atmospheric composition. On time scales of months to years, it is primarily the changes in surface conditions that provide predictability. Of those, the changes in regional patterns of sea surface temperatures (SSTs) constitute the most persistent influence on the atmosphere. This means that if we can understand more about the mechanisms that control sea surface temperature and ocean currents, we may start to unravel some of the mysteries of climate prediction beyond our current very limited time frame of about a year.

On time scales of decades and longer, it is changes in energy retained by the ocean and atmosphere due to increasing greenhouse gasses (GHGs) that will exert the greatest influence on climate, such as increasing global temperatures. At the scale of several years to decades, the influences of SSTs and GHGs overlap, and both will contribute in interdependent ways to changes in climate. In this article, we focus mainly on the climate variability attributed to patterns in SSTs, although the influence of climate changes due to increasing concentrations of GHGs on these patterns cannot be ignored. Changes in the climate system due to increasing GHGs may also influence the character of natural SST-related variability, which is a significant challenge for those who are trying to understand the already-complex decadal-scale patterns.
A relatively small handful of oceanic phenomena, identified by large-scale changes in SSTs, have been impli-

Figure 1.
Observed sea surface temperatures (SSTs) during the peak of one of the largest El Niño events of the 20th Century.



cated in regional temperature and precipitation variations across the globe. Of these, the El Niño-Southern Oscillation (ENSO) phenomenon of the tropical Pacific is by far the most understood and best predicted. Decadal variability, such as the Atlantic Multi-decadal Oscillation (increasingly referred to more generally as Atlantic Multi-decadal Variability) and the Pacific Decadal Oscillation (similarly becoming Pacific Decadal Variability) exhibit stronger variations in the mid-latitude oceans and act over much longer timescales than ENSO. Currently our understanding of decadal variability phenomena is limited, and our ability to predict them is in its infancy. All of these (ENSO, PDV, AMV) appear to impact temperature and precipitation patterns over the United States. In the next sections, we describe these slowly varying fluctuations in the ocean more thoroughly, addressing the questions: What do they look like? What are the associated timescales? What is our understanding of what causes them? What is our evidence of how they impact climate over California? And, can we predict them?

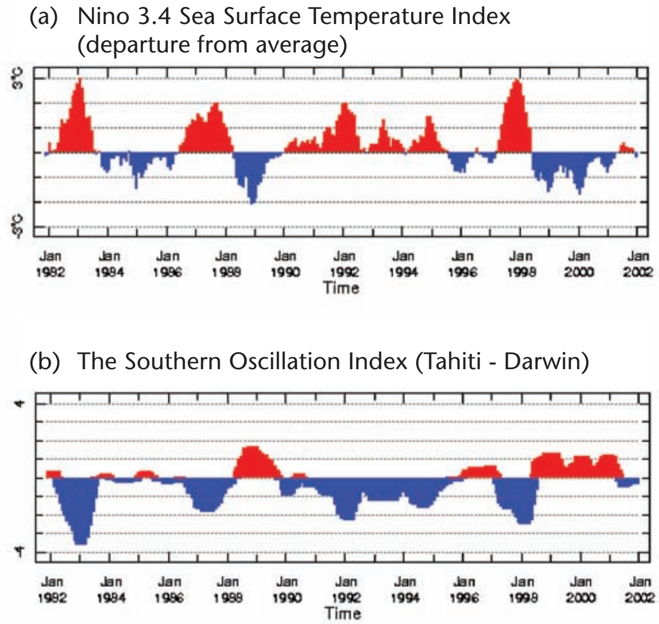
El Niño-Southern Oscillation (ENSO)

ENSO is observed as a periodic warming or cooling of the central-eastern equatorial Pacific. ENSO events are quasi-periodic, which means that they have a preferred frequency – of about 4 years – but are not regular, and rather occur approximately every 2-7 years. Warm and cold ENSO events tend to be in sync with the annual cycle. They typically start to develop in northern hemisphere spring and reach their maximum amplitude near the end of the year. Strictly speaking, El Niño represents the warm phase of ENSO in the ocean, and La Niña refers to the cold phase when the central-eastern tropical Pacific becomes colder than normal. Figure 1 shows the observed differences in SSTs during the 1982 El Niño as compared to average conditions.

The "Southern Oscillation" refers to changes in sea level pressure differences between east and west tropical Pacific associated with ENSO. Unusually warm water in the central-eastern Pacific leads to heavy rainfall over this region. As the region of heavy rainfall moves from the western Pacific into the central Pacific, the sea level pressure in the western Pacific increases, and the sea level pressure in the central-eastern Pacific drops. Since the Southern Oscillation Index (SOI) measures the difference in atmospheric pressure between Tahiti and Darwin Australia, during El Niño the SOI decreases. The status of ENSO is commonly tracked with the NINO3.4 index that measures the changes in SSTs within a region of the equatorial central-eastern Pacific. The time series of SOI and NINO3.4 are strongly anti-correlated (Figure 2), so either index provides a useful means for tracking ENSO conditions.

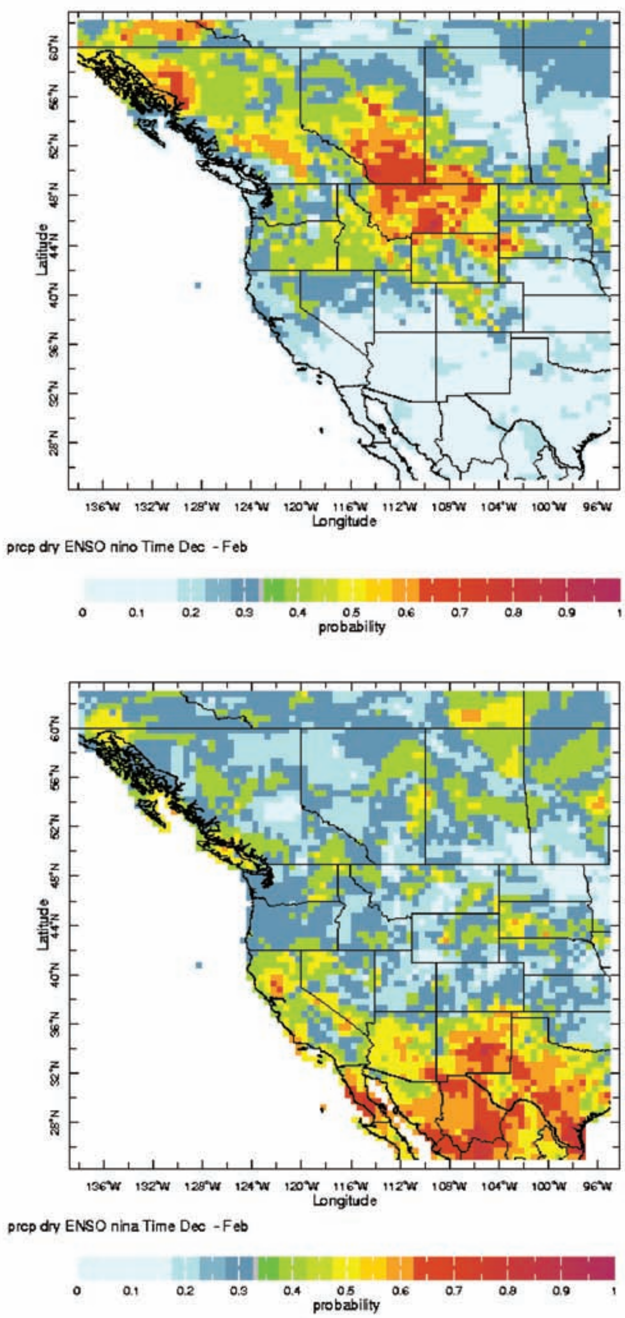
The changes in SSTs influence the winds, which then affect the structure of the upper 100-200m of the tropical ocean. This generates very long waves, tens of thousands of kilometers long, traveling east and west at 50-150m below the surface of the ocean. These waves can lead to growth of an incipient ENSO event, for example by moving more warm water westward or reducing the normal cooling effect of equatorial upwelling currents during an El Niño. At the same time, the changes in the upper ocean structure plant the seeds for the demise of that event and initiation of the opposite phase. In this way it is possible for the system to naturally oscillate between El Niño and La Niña conditions. Generally speaking, it is only once a large-scale temperature change exists in the slowly evolving ocean structure that predictions at lead times of months or a few seasons into the future are possible.

Figure 2.
Time series of ENSO indices. (a) NINO3.4 index, measuring the average SST anomaly within the box 5S-5N; 170W-120W; (b) Southern Oscillation Index (SOI), measuring the difference in standardized sea level pressure anomaly between Tahiti and Darwin, Australia.



Although precipitation conditions in parts of North America are correlated with ENSO events (Figure 3 shows the likelihood of dry winters during El Niño and La Niña conditions), simple historical analyses indicate that conditions during a particular event may deviate from expectations (McCabe and Dettinger, 1999; Trenberth and Stepaniak, 2001). Differences in the strength, structure or timing of the event, in addition to influences from other parts of the climate system, lead to differences in local and even regional climate anomalies during ENSO events The recognition of the variable nature of each event has given rise to the term "the flavors" of ENSO.

Figure 3.
Frequency (number of cases out of 10 ENSO events) that observed Dec-Jan-Feb precipitation was in the driest 1/3 of the historical record. So, orange to red colors suggest enhanced risk of a dry season during (a) El Niño and during (b) La Niña. (Based on analysis of Mason and Goddard, 2001)



Pacific Decadal Variability

Based on analyses of historic climate records fom the past 100 to 150 years, and proxy climate records for the past few centuries, it is now clear that the climate of the Pacific and surrounding continents has patterns that evolve over time frames of one to many decades. The Pacific Decadal Oscillation, or PDO, is the most widely recognized pattern of Pacific Decadal Variability. The PDO has been described as a long-lived ENSO-like pattern of Pacific climate variability because the two climate oscillations have similar spatial patterns in SST and sea level pressure but very different time scales. Two main characteristics distinguish PDO from ENSO:

1) 20th century PDO "events" persisted for 20-to-30 years, while typical ENSO events persisted for 6 to 18 months;
2) The strongest regional climate anomalies associated with the PDO are found in the North Pacific/North American sector, with weaker impacts seen in the tropics. The opposite is true for ENSO.

Several independent studies find evidence for just two full PDO cycles in the past century: "cool", or "negative", PDO regimes prevailed from 1890-1924 and again from 1947-1976, while "warm", or "positive", PDO regimes dominated from 1925-1946 and from 1977 through (at least) the mid-1990's. Figure 4 shows SST's and sea level pressure as related to the PDO index.

The mechanisms for PDV are not clear, and there is an increasing body of research on this question, including paleo reconstructions. Identifying the mechanisms giving rise to Pacific Decadal Variability (PDV) will determine whether skillful multi-year to decades-long PDV climate predictions are possible. For example, if aspects of the PDO arise from air-sea interactions that take 10 years to develop, then aspects of the phenomenon will (in theory) be predictable at lead times of up to 10 years. Even in the absence of a theoretical understanding of the mechanisms that cause these phenomena, information about PDV can improve season-to-season and year-to-year climate forecasts for North America because of the strong tendency for multi-season and multi-year persistence. This persistence has significant implications for water managers.

The period since the late 1990s has been difficult to characterize as being either a positive or a negative PDO regime, and this raises one of the most important issues for understanding and predicting the PDO and other aspects of PDV. Without a better handle on the mechanisms that give rise to these phenomena, we cannot know exactly what part of the climate system we should be measuring in order to even determine the current phase of a decadal climate pattern, and we cannot be sure that our climate

Figure 4.
Patterns of Sea Surface Temperature (color shading) and Sea Level Pressure (contours) associated with (a) the Pacific Decadal Oscillation (PDO); and the cold tongue index (CTI), which is very similar to the NINO3.4 index of ENSO for the period 1900-1992. Contour interval is 1mb, with additional contours draw for +-0.25 and 0.50 mb. Positive (negative) contours are dashed (solid). These patterns are indicative of the positive phase of the PDO and ENSO, respectively. (From Mantua et al, 1997)

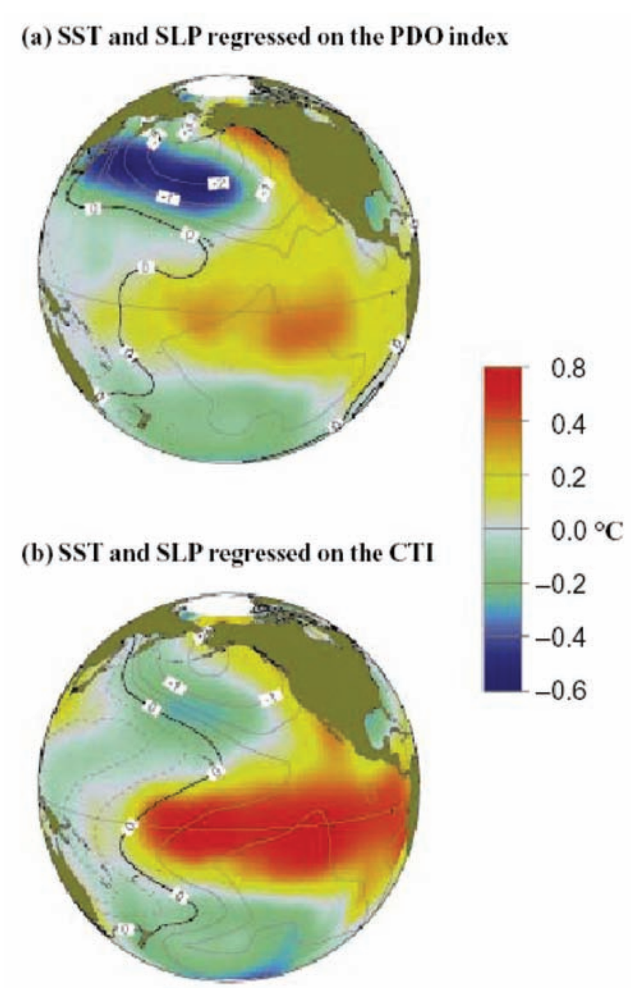
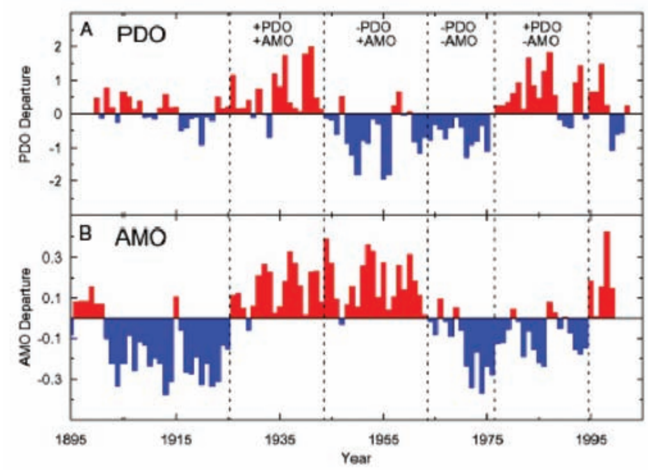
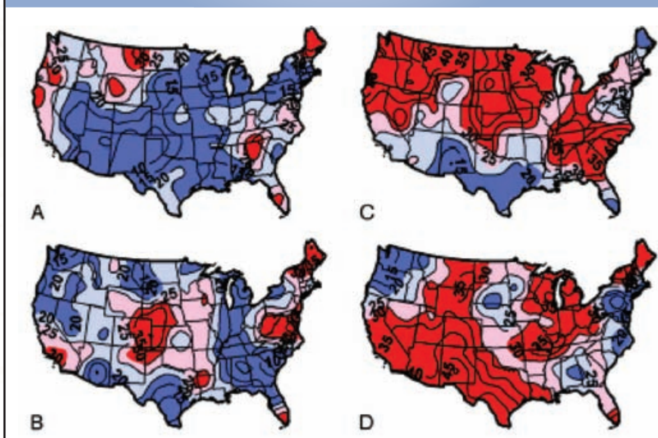


Figure 5.
Time series of the annual (A) Pacific Decadal Oscillation (PDO), and (B) Atlantic Multi-decadal Oscillation (AMO). (From McCabe et al, 2004)



continental U.S. Prolonged wet-spells over much of the continental U.S. from 1905-1930, the 1940s, and from 1976-1995 mostly coincided with periods of relatively cool North Atlantic Ocean temperatures. An AMO index is based on annual average ocean surface temperatures for the Atlantic Ocean from the equator to 70°N latitude. The AMO index was negative in all but one year from 1902-1925, positive in most years from 1926 to 1964, negative in most years from 1965 to 1994, and

Figure 6.
Drought frequency, in percentage of years (where “drought” is defined as annual precipitation is the driest 25% of years for the period 1900-1999) for positive and negative regimes of the Pacific Decadal Oscillation (PDO) and Atlantic Multi-decadal Oscillation (AMO). (A) Positive PDO, negative AMO. (B) Negative PDO, negative AMO. (C) Positive PDO, positive AMO. (D) Negative PDO, positive AMO. (From McCabe et al, 2004). See Figure 5 for time periods corresponding to these combinations of PDO and AMO phases.



modeling and prediction tools are adequate for making forecasts that have the level of “skill” needed to support improved decision-making by water resource managers.

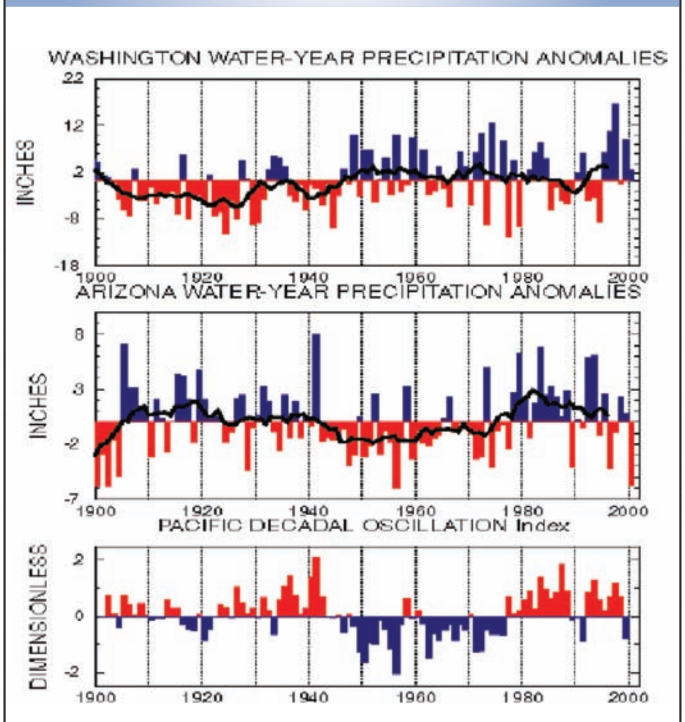
Atlantic Decadal Variability

As in the Pacific sector, analyses of history and proxy climate records has revealed the existence of long-lived climate pattern related to changes in the Atlantic Ocean. The Atlantic Multidecadal Oscillation (AMO) is the label given to observed changes in climate associated with the average surface temperatures for the North Atlantic Ocean. Variability in the AMO has been linked with multidecadal changes in precipitation and stream flow in the mostly positive from 1995 to present (Figure 5). There is no certainty about the mechanisms that drive the AMO, although this is increasingly a topic of study. Further, the teleconnections between conditions in the Atlantic and climate in the western U.S. are not well understood. Nevertheless, the two leading patterns of 20th century decadal drought over the U.S. closely track the decadal changes in the AMO and PDO indices (Figure 6). Prolonged dry spells in the 1930s, the 1950s-1960s, and from 1996-2004 coincided with positive phases of the AMO. During these dry spells, changes in the phase of the PDO pattern corresponded with north-south shifts in drought areas resulting in drought concentrated in the northern U.S. for positive PDO periods that shifted to the southwestern U.S. during negative PDO periods. For Southern California and the Southwest U.S., this combination of a warm North Atlantic (and positive AMO) along with a cool (or negative) phase of the PDO has historically favored prolonged dry spells.

Ocean Influences on California Water Supplies

River inflow into the major reservoirs in California is driven primarily by spring snowmelt in the mountain ranges of the Sierra Nevadas and Oregon's southern Cascades, and many rivers also derive flow from winter precipitation. Coupled with dry summers, these runoff dynamics produce a marked seasonal cycle in river flow that peaks in most locations in the late spring and early summer. The role of snowmelt in California hydrology means that both winter precipitation and winter and spring temperatures play a central role in determining the hydrologic outlook of each water year (October through September).

Figure 7.
Comparison of water year precipitation anomalies in Washington and Arizona with PDO variations.
From Schmidt and Webb, (2001).



In the western US, precipitation and temperature variations have been linked to variations in the ocean circulation associated with ENSO, PDO, and other indices (Figure 2; also Pierce, 2005; Cayan et al., 1999; Quan et al., 2006, among others). Figure 7, for instance, shows that in the past century, the states of Washington and Arizona have experienced precipitation variability that somewhat corresponds, but with opposite sign, to variations in the PDO. Similar linkages have been found for river basins throughout the western US, and the analysis of Graumlich et al. (2003) provides a good example (focusing on the Yellowstone River of Wyoming, Montana and Idaho) from this body of work.

In California during the winter, ENSO has a stronger linkage to precipitation in the south and to temperature in the north, although the variance explained by ENSO patterns is less than 25 percent. Winter temperature has a relatively stronger linkage to PDO, particularly to the north, but the PDO has only a weak influence on winter precipitation throughout the state. The association of the AMO with winter temperature is generally weaker than that of the PDO, and concentrated in the center of the state. The AMO has very little correlation with California's winter precipitation. Among other indices of Pacific climate variability, the North Pacific Index (NP) of Trenberth and Hurrell (1994) has received recent attention as perhaps the strongest connection to winter temperatures in California, but it has a weaker association with winter precipitation. The NP is based on sea level pressures, and given that it is one step closer to the wind/weather patterns that influence western N. America than any SST index, it is better correlated with aspects of west coast winter climate than is the SST-based PDO index. The winter NP is strongly correlated (greater than 0.75) with the PNA atmospheric pattern that is related to the PDO, and is moderately correlated with the PDO (0.5 to 0.6).

A number of studies (e.g., Maurer et al., 2004; Piechota and Dracup, 1999; Piechota et al., 1997) have catalogued the streamflow or hydrologic predictive skill by season and location for ENSO, PDO, AMO and other circulation indices. Table 1, adapted from Maurer et al.,

Table. 1

Statistically significant correlations exist in winter and spring between runoff (hence streamflow) in the Southwest and Mexico and various indices of ocean and atmospheric circulation. The signs in parentheses after the index identifiers show the direction of the correlation (positive, negative, or both, depending on location - from Maurer et al. 2004).

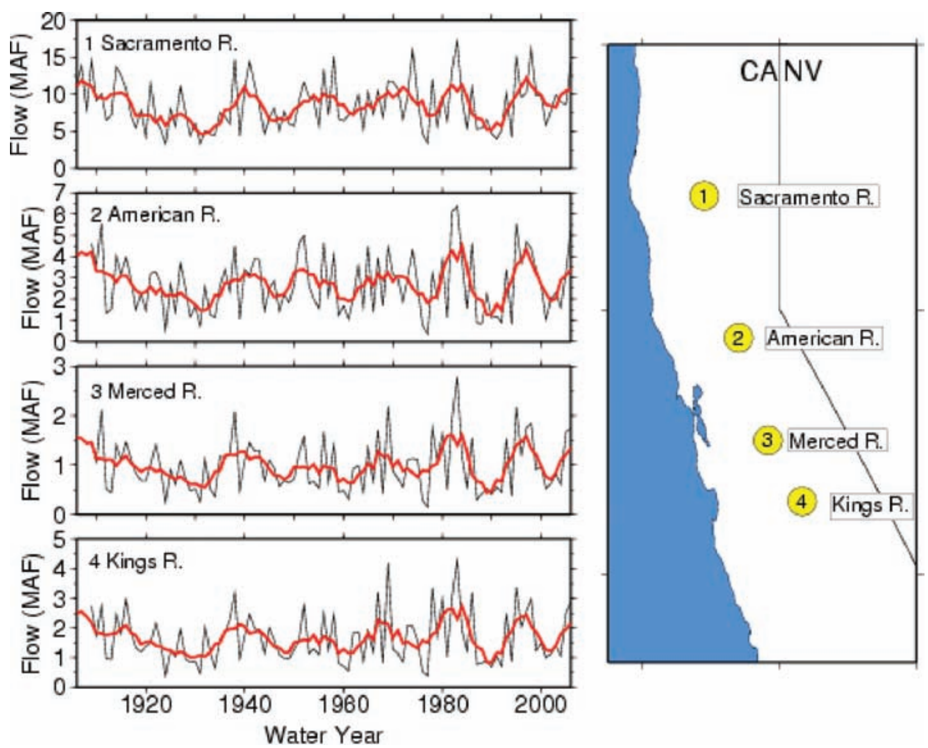
Target Projection Season	Lead Time (seasons)				
	zero	one	two	three	four
Dec-Jan-Feb (winter)	NP(-)	Nino3.4(-)	PDO(-), AMO(+)	PDO(-)	PDO(-), AMO(+)
Mar-Apr-May (spring)	Nino3.4(±), PDO(-)	AO(+), NAO(-), Nino3.4(±)	Nino3.4(-)	Nino3.4(-), AMO(+)	AMO(+)

2004, indicates that for a region including most of California, the strength of these connections varies by lead time. The existence of significant correlations at lead times of up to 4 seasons indicates potential hydrologic predictability that might be leveraged from improved predictions of these features of the ocean-atmosphere circulation.

A few studies have demonstrated decadal-scale variation in both ENSO and the linkage of ENSO to western US climate. McCabe and Dettinger (1999) for instance, found that the linkage between summer-to-fall ENSO indices and October-March precipitation was stronger during warm PDO years than in cold PDO years, despite significant variation in the strength of this linkage within

Figure 8.

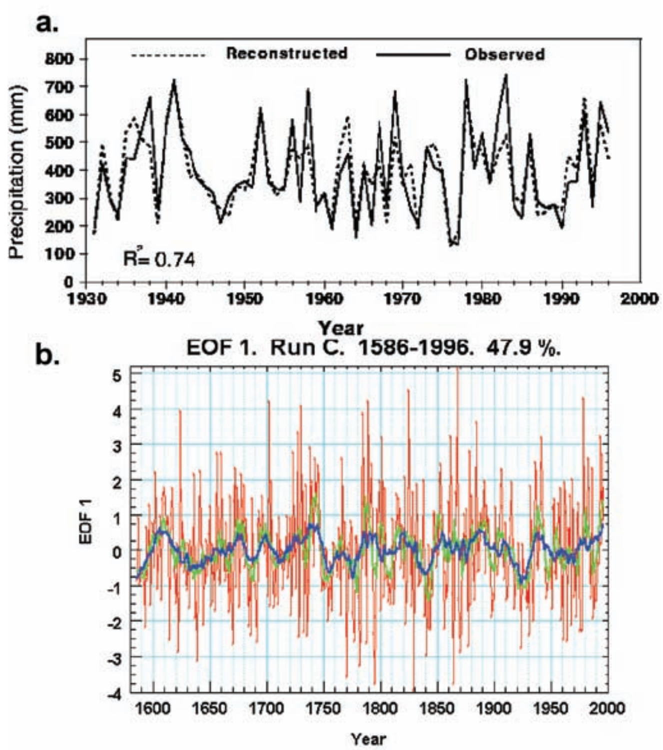
Observed flow in four major California rivers. Thin lines show water year streamflow, and thick lines show 5-year moving averages. California Data Exchange Center station IDs are SBB, AMF, MRC, KRG, in north to south order.



either category of years. The interaction between the decadal-scale variation in PDO with ENSO-climate linkages underscores the need to extend current research from the seasonal to inter-annual dynamics associated with ENSO to decadal time-scales.

Like much of the western US, California's climate and hydrology exhibit variability ranging from the interannual to decadal, as well as longer-lived (e.g., oscillations playing out over a few to many decades). At the shorter period end of this range (seasonal to decadal), observational records of precipitation, snow and streamflow from the last century offer a perspective on this variability, and on the linkages of western US hydroclimatic variability to ocean circulation. For example, Figure 8 shows the annual flow in four major California rivers during the last century. All four flow records reflect a superposition of interannual variability that is partly related to ENSO,

Figure 9.
(a) Tree-ring based reconstruction of Central Valley precipitation from the 1930s to present. (b) Tree ring record behavior extended back to the mid 16th century. From Redmond et al. (2002).



partly to a decadal-scale variability that produces periods of 5-10 years of mean flow departures from normal, and possibly to longer term variability or trends. Dry and wet multi-year periods show a strong temporal correspondence in the four streamflow locations throughout the century, and in each, the droughts of 1929-34, 1976-77, and 1987-92, which were all important from a water supply standpoint, are easily detectable.

The observed record for climate and streamflow from the 20th century contains fewer than a half dozen decadal-scale cycles, hence the potential offered by these measurements for description of hydrologic and climatic variability at decadal and longer frequencies is limited. For such investigations, researchers turn to proxy reconstructions (e.g., of tree rings – dendrochronology) to extend the perspective on variability back hundreds of years before the last century. Because of the strong linkage of annual tree growth to variations in precipitation, streamflow, drought occurrence and, in the western US, snowpack, tree ring chronologies are a primary data source for climate, drought and flow variable reconstructions that can span 500 years or longer. The NOAA National Climatic Data Center Paleoclimatology Branch provides a central location in the US for access to California-focused findings and data related to this research (see http://www.ncdc.noaa.gov/paleo/streamflow/ca/).

Reconstructed precipitation, streamflow and other variables are first calibrated and validated during the period of the observational record and then extended to periods preceding the calibration and validation data. Figure 10a shows an example of the close correspondence that can be achieved between reconstructed variables, in this case Central Valley precipitation, and observations. This supports the theory that the variability shown in the extended tree ring record (Figure 9b) can be transferred to the hydroclimatic variable of interest. Fritts (1965) applied dendrochronology to identify extended, multi-decadal dry periods in the interior west, revealing approximately 15 decadal-scale dry periods in California between 1500 to 1940, with notable periods before the 20th century being 1771-1790 and 1851-1865. More recently, Earle (1993) found that decadal-scale excursions from normal conditions have been a regular feature of northern California streamflows, in a reconstruction extending back to the 1560. Figure 10, based on data from Meko et al. (2001), shows reconstructed Sacramento River flow back to AD 869. This work suggests that decadal variability has been influencing water supplies for thousands of years.

Research Needs for Improving the Potential for Longer-term Predictions

Since much of the predictability of decadal variability depends on understanding and monitoring the slow changes in the ocean circulation, thorough observations of the ocean are critical to dynamical predictions. Thorough observations are critical even to identifying the current

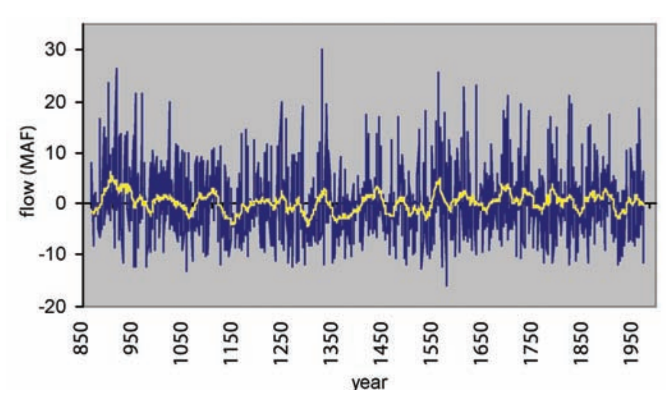


Figure 10.
Tree-ring based reconstruction of Sacramento River flow expressed as departure from the mean from the year 869 to 1977. Data from Meko et al. (2001).

state of the oceanic phenomena. The observing system needed to measure the structure of the ocean density and currents at depth has only recently come into existence. An array of floats, known as ARGO (http://www.argo.net/), now regularly measures temperature and salinity at depths up to 2000m, but this network has only become sufficient to describe the 3-dimensional structure of the ocean in the last few years. This information on ocean structure supports dynamical models of the ocean; it is the inertia, or relative imbalance, in the ocean's distribution of mass, that provides an indication of future evolution in the oceanic circulation. The atmosphere's response and feedback to changes in the SST patterns is what allows the atmospheric models to suggest how regional climate would likely respond to the slow changes in ocean circulation.

We do not know what controls decadal scale variability. There is a need to combine instrumental, paleo, and model data to investigate the dynamics behind PVD and AMV. Once we have a better understanding of the mechanisms that cause the variability, our capacity to predict future conditions based on analysis of current conditions and trends will improve dramatically. Dynamical ocean and ocean-atmosphere models and the methods used to employ the observations that initialize them still require substantial improvement before their predictions of ocean evolution years into the future can be used with confidence. Global ocean models currently have low resolution, typically 100km or more horizontal spacing between grid points where the physical equations are evaluated, and many important aspects of mixing and diffusion in the ocean are not properly captured. The advent of improved observations should aid these deficiencies in the models. Perhaps related to this, the timescales of "natural" variability in the models, from ENSO to AMV, rarely match the observed timescales of these phenomena. As a result, the use of dynamical models to understand the mechanisms behind these phenomena is almost as limited as the ability of those models to predict decadal variability. Several operational centers, mainly in Europe, are currently experimenting with decadal prediction systems, but the models remain limited in their ability to react to the initial ocean state, relative to the imposed changes in GHGs (Troccoli and Palmer, 2007; Smith et al., 2007).

The current mismatch between our ability to predict climate and the demand for long lead climate predictions is a source of frustration for water managers. It may be another 5-10 years before the dynamical models can predict natural decadal climate variability, yet that does not mean that no information is available. Two obvious sources of information can be mined now. The first source of information lies in the observed historical record. Given the long timescale involved here, data records based on proxies (such as tree rings or lake levels) and matched to the current instrumental record offer the greatest promise for describing the range of variability occurring on decadal timescales. The second, a likely result of humankind's industrial activity, is the slowly unfolding reality of human-caused climate change. Thus, given no additional information on the specific evolution of natural decadal variability in the coming 10 years, one could specify the range of historical variability, while recognizing that it rides atop trends associated with human-caused climate change. In some cases, it may be possible to augment this information with statistical extrapolation of identified local periodic variability (Robertson et al., 2001), or to be more specific about at least the next several years based on persistence or prediction of dynamics like the PDO (Newman, 2007). Then information on the seasonal-to-interannual variability may further adjust expectations in the coming 6 months based on ENSO or other seasonal predictor forecasts.

A number of efforts are under way, within the United States and internationally, that aim to better understand and better predict variability at lead times longer than one year into the future. Several workshops were convened recently (see http://usclivar.org and link to Seattle BOR workshop), seeking to bring the observational and dynamical modeling communities closer together, and accelerate progress on decadal prediction in the Atlantic. US CLIVAR is currently developing a 2-year working group on decadal predictability, the scope of which is yet to be determined.

Key research questions that arose in the context of the recent workshop sponsored by the US Bureau of Reclamation and the Water Resources Research Center at the University of Arizona in the context of research to enhance the use of climate information in managing the Colorado River included the following:

- What is the role of the land surface, particularly in the persistence of drought conditions? Is it significant for decadal time scale patterns of climate variability? Interaction of moisture sources on the land need to be understood, especially in the western U.S..
- Is persistence of climate conditions recognizable and is it predictable? What are the mechanisms of persistence? Water managers are most concerned about our ability to predict transitions from one climate condition to another.
- Can we identify which physical mechanisms drive the impacts that key users care about (water managers, fisheries, fire managers, and so forth)? This should inform the observational (monitoring) priorities for supporting a decadal prediction system.
- Can we quantify the amplitude of the anthropogenic signal vs. natural variability? This is important for identifying future trends in water supply and in predictive capacity. For example, what will the impacts of human-caused climate warming be on ENSO?
- Can we better articulate our increasing understanding of how changes in the ocean circulation connects with changes in the location of storm tracks, changes in atmospheric circulation and abundance of water vapor?

It is clear that many of these concerns resonate with and provide motivation for the scientific questions and research priorities described in this document.

Conclusions

Much progress has been made in understanding climate in the 130 years since John Wesley Powell informed Congress that the subject was still "unknown", but not "unknowable". Most of this progress has been concentrated on comprehending daily to seasonal variations, and the ability to predict climate conditions beyond one year is still in its infancy. Yet there are strong economic and social reasons why working on decadal climate prediction should be a high priority research investment. It is clear that we can reduce risks related to water supply availability with better information about the likelihood of wetter vs. drier years, especially given our understanding of the seasonality of precipitation. The high priority questions that need further research are emerging from a series of conversations between researchers and water managers. The critical question now is whether funding can be found to support this important work.

References

Cayan, D.R., K.T. Redmond, and L.G. Riddle, 1999, ENSO and hydrologic extremes in the western United States, J. Climate 12, 2881-2893

Earle, C. J.: 1993, Asynchronous Droughts in California Stream-Flow as Reconstructed from Tree Rings, Quatern. Res. 39, 290–299.

Graumlich, L.J., M.F.J. Pisaric, L.A. Waggoner, J.S. Littell and J.C. King, 2003, Upper Yellowstone River Flow and Teleconnections with Pacific Basin Climate Variability during the Past Three Centuries, Climatic Change 59:1-2, 245-262, DOI 10.1023/A:1024474627079

Hidalgo, H. G. (2004), Climate precursors of multidecadal drought variability in the western United States, Water Resour. Res., 40, W12504, doi:10.1029/2004WR003350.

Kalnay, E. and Coauthors, 1996: The NCEP/NCAR Reanalysis 40-year Project. Bull. Amer. Meteor. Soc., 77, 437-471.

Mantua, N. J., S. R. Hare, Y. Zhang, J. M. Wallace, and R. C. Francis, 1997. A Pacific interdecadal climate oscillation with impacts on salmon production. Bull. Amer. Meteor. Soc., 78, 1069-1079.

Mason, S. J. and L. Goddard, 2001. Probabilistic precipitation anomalies associated with ENSO. Bull. Amer. Meteor. Soc., 82, 619-638.

McCabe, G. J., M. A. Pakecki, and J. L. Betancourt, 2004. Pacific and Atlantic Ocean influences on multi-decadal drought frequency in the United States. Proc. Nat. Acad. Sci., 101, 4136-4141.

Meko, D.M., M.D.Therrell, C.H.Baisan, and M.K Hughes, 2001. Sacramento River flow reconstructed to A.D. 869 from tree rings: Journal of the American Water Resources Association 37(4): 1029-1040.

Newman, M., 2007. Interannual to decadal predictability of tropical and North Pacific sea surface temperatures. J. Climate, 20, 2333-2356.

Nilsson, C., C. A. Reidy, M. Dynesius, C. Revenga, 2005, Fragmentation and Flow Regulation of the World's Large River Systems, Science 308, 405-408.

Maurer, E. P., D. P. Lettenmaier, and N. J. Mantua (2004), Variability and potential sources of predictability of North American runoff, Water Resour. Res., 40, W09306, doi:10.1029/2003WR002789.

McCabe, G.J. and M.D. Dettinger, 1999. Decadal variations in the strength of ENSO teleconnections with precipitation in the western United States, International J. of Climatology 19:13, 1399-1410, DOI: 10.1002/(SICI)1097-0088(19991115).

Piechota, T.C., and J.A. Dracup, 1999. Long Range Streamflow Forecasting Using El Niño-Southern Oscillation Indicators. Journal of Hydrologic Engineering, 4(2), 144-151.

Piechota, T.C., J.A. Dracup, and R.G. Fovell, 1997, Western US streamflow and atmospheric circulation patterns during El Niño-Southern Oscillation, J. Hydrol. 201, 249-271.

Pierce, D.W., 2005, Effects of the North Pacific Oscillation and El Niño-Southern Oscillation on Seasonally Averaged Temperatures in California, Report: CEC-500-2005-002, Feb-05, to the California Energy Commission.

Redmond, K.T., D.W. Stahle, M.D. Therrell, D.R., Cayan, M.D. Dettinger, 2002. 400 Years of California Central Valley precipitation reconstructed from blue oaks. Preprint, 13th AMS Symposium on Global Change and Climate Variations, Orlando FL, 13–17 January 2002, pp. 20-23.

Robertson, A. W., C. R. Mechoso, and N. O. Garcia, 2001. Interannual prediction of the Parana River. Geophys. Res. Lett., 28, 4235-4238, doi: 10.1029/2000GL012197.

Schmidt, K.M., and Webb, R.H., 2001, Researchers consider U.S. Southwest's response to warmer, drier conditions: Eos, Transactions, American Geophysical Union, v. 82, p. 475, 478.

Smith, D.M., S. Cusack, A.W. Colman, C.K. Folland, G.R. Harris and J.M. Murphy, Improved Surface Temperature Prediction for the Coming Decade from a Global Climate Model, Science 317:5839, 796 – 799, DOI: 10.1126/science.1139540.

Trenberth. K.E. and J.W. Hurrell, 1994: Decadal Atmosphere-Ocean Variations in the Pacifc. Climate Dynamics: Vol. 9, pp.303-319.

Trenberth, K.E., and D.P. Stepaniak, 2001: Indices of El Niño Evolution. J. Climate, 14, 1697–1701.

Troccoli, A. and T. N. Palmer, 2007: Ensemble decadal predictions from analysed initial conditions. Phil. Trans. R. Soc. A, 365, 2179-2191, 10.1098/rsta.2007.2079.

Changes in Aridity in the Western United States

Hidalgo H.G.[1], Dettinger M.D.[2] and Cayan D.R.[3]

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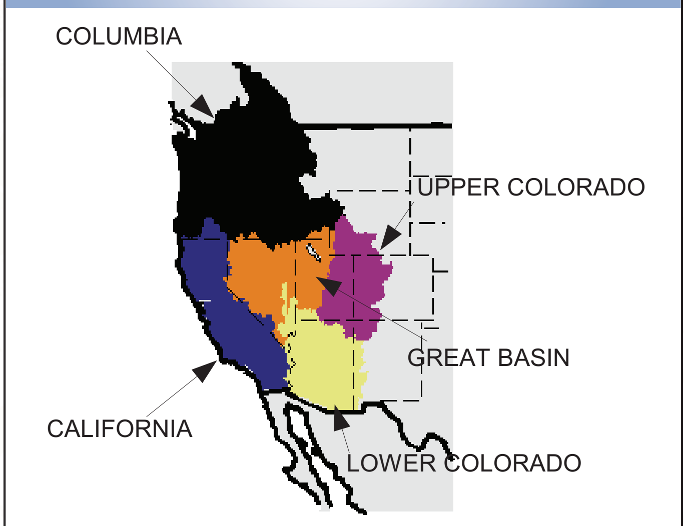
Introduction

It is often remarked that most of the western US (Figure 1) is "always in drought," especially by visitors from wetter climates. The plants and landforms of the West, however, are more or less adapted to the region's relatively dry but variable climates, and so important variations in the levels of drought, or aridity, characterize the landscape. During "real" droughts, broad areas of the West are subjected to drier conditions than normal, imposing—at least temporarily—arid climatic conditions on many semiarid and even humid areas. In response to these climatic conditions, the hydrologic balances between waters that run off and those that evaporate back into the atmosphere are transformed temporarily in ways that color the entire region's water supplies and vegetation. In this article, we describe the major changes that droughts wreak on the "normal" partitioning of precipitation between evaporation and runoff, as depicted by a hydrological model that simulates historical variations of the region's surface hydrology.

Actual evapotranspiration (AET) is the combined flux of water to the atmosphere from soil surfaces and plants by evaporation and through plants by transpiration. AET depends on the availability of both water and energy. Potential evapotranspiration (PET) is the atmospheric demand of water from the soil and free water surfaces, and represents the amount of evapotranspiration that would occur if water were not a limiting factor. A body of previous research has demonstrated that there are well-defined connections between droughts and the ratio of AET/PET in the western US. This ratio is called evaporative efficiency or ß. Extremely low values of are common in arid regions where PET is high and lack of water limits AET rates. High values of ß occur in semi-humid and humid regions (usually at the top of the mountains in the West), where energy availability limits AET rates. Intermediate values of ß, when the annual demand for water is considerably higher than the supply of water but not as strong as in the arid regions, occupy the largest part of the western US; these regions are classified as "water limited" and include areas that are often described as semi-arid.

Figure 1.
Location of principal "basins" of the western US



"Green water" is a name given to AET by Falkenmark and Rockström (2004), with "blue water" the name given to the remaining fraction of water that is not consumed by evapotranspiration (P-AET). Blue water is thus the water that runs off into streams or recharges into aquifers. A key point in this article is how drought shifts the flow of water from blue to green. Even as it shifts water from blue outflows to green uses, in most cases, drought reduces the overall availability of water for evapotranspiration in a region, lowering the AET efficiency along with the total AET. This results in temporary increases in the aridity (as measured by ß) in the drought-affected region. Thus during a drought, regions that are semiarid on long-term average can experience hydro-climatic conditions similar to the ones normally found in arid regions. Similarly, during droughts, regions in which AET is energy-limited, on long-term average, can become water limited (or even extremely water-limited). The temporary increase in aridity of a region can have severe impacts on ecological systems in general, wildfire potential and soil erosion. This article also investigates the geographic extend of the changes in aridity conditions during droughts and pluvials.

VIC Model and Data Sources

Hydrological fluxes and conditions simulated by the Variable Infiltration Capacity (VIC) macroscale land-surface hydrological model--originally developed at the University of Washington and Princeton (Liang et al. 1994)--provide the raw materials for the results presented here. VIC has been used extensively in a variety

[1] University of California San Diego (UCSD)
[2] UCSD, USGS
[3] UCSD, USGS

of water resources applications; from studies of climate variability, forecasting and climate change studies (e.g. Wood et al. 1997; 2004; Hamlet et al. 1999; Nijssen et al. 1997; 2001). The model's soil moisture estimations produce reasonable agreement with the few point measurements available, while VIC-simulated runoff validates well with observations when the model has been calibrated using streamflow data, giving us confidence that VIC results provide a useful depiction of how drought changes the area's water budgets. Daily AET values were obtained directly from the model's output while PET was computed from net radiation and relative humidity from VIC, and temperature and windspeed from the Hamlet and Lettenmaier (2005) dataset, using a Penman-Monteith equation (Penman 1948; Monteith 1965) as described in Shuttleworth (1993). For each gridpoint, PET was estimated as the weighted sum of the daily contributions from all vegetation types, including bare soil. The period of the simulations used here are from 1950 to 2003.

AET Efficiency

A classification of the West into regions with long-term average energy-limited, water-limited and extremely water-limited AET conditions is shown in Figure 2a. A limit of ß=0.63 was used as the threshold between energy-limited and water-limited AET regions in this article, because it corresponds empirically to western settings where annual-mean P is equal to annual-mean PET (Hidalgo et al. 2007). Regions with less than 0.2 are labeled regions of extremely water-limited or arid regions, according to Rind et al. (1990) and Hidalgo et al. (2007). With these definitions, energy-limited areas are located mainly in the high elevations of the West and in the coastal regions of Washington, Oregon and Northern California, accounting for 19% of the western US. Water limited regions fall in between the energy limited and arid regions, and occupy the largest fraction (51%) of the region. Most of the southern deserts, the low elevations of the Upper Colorado River Basin (UCRB) and the rain shadowed parts of Washington are classified as arid, accounting for 30% of the region.

From year to year, though, application of these same thresholds indicate large variations in the extents and locations of the three ß categories, as can be seen in the aridity maps for the 2002 drought and the 1983 pluvial (Figures 2b-c). In the drought-year 2002, low ß values, low enough to fall into the arid category, expanded to occupy 51% of the region, indicating widespread aridity conditions similar to those normally found in deserts. Conversely, in the wet year 1983, the arid category was reduced to only 15% of the West, and energy-limited conditions spread to 29% of the West.

The long-term ß regions shown in Figure 2a experience (and reflect) different long-term average seasonal cycles of hydroclimate (black curves, Figure 3). Precipita-

Figure 2.
Annual distribution of areas with energy-limited evapotranspiration (black), water-limited evapotranspiration (white) and extremely water-limited or arid regions (yellow).

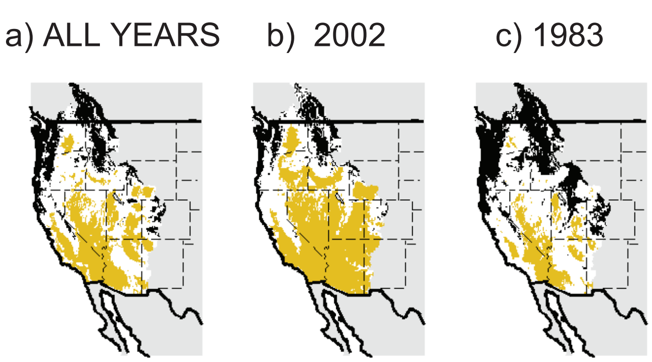
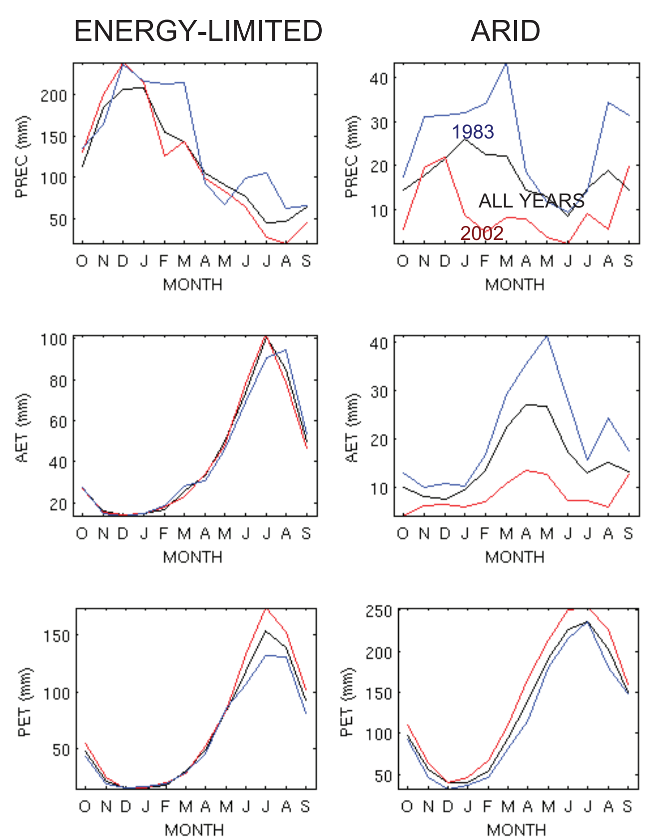


Figure 3.
Climatologies of precipitation (P), actual evapotranspiration (AET), and potential evapotranspiration (PET) for regions of high AET/PET ratios. The climatologies were computed using the regions defined in Figure 2a.



tion (Figure 3, top panels) and runoff (not shown) are considerably larger in the energy-limited regions and tend to continue until later in the year. The energy-limited regions tend to exhibit later AET peaks (Figure 3, middle panels) because water persists in the soils longer from the greater spring-summer soil-moisture reserves of wintertime snow. Although PET is somewhat higher in the arid and semi-arid regions than in the energy-limited regions, the values are still the same order of magnitude as in the water-limited regions. Therefore it is the supply of water that makes the largest difference in determining aridity patterns, while the demand for water by ET plays a secondary but not inconsequential role.

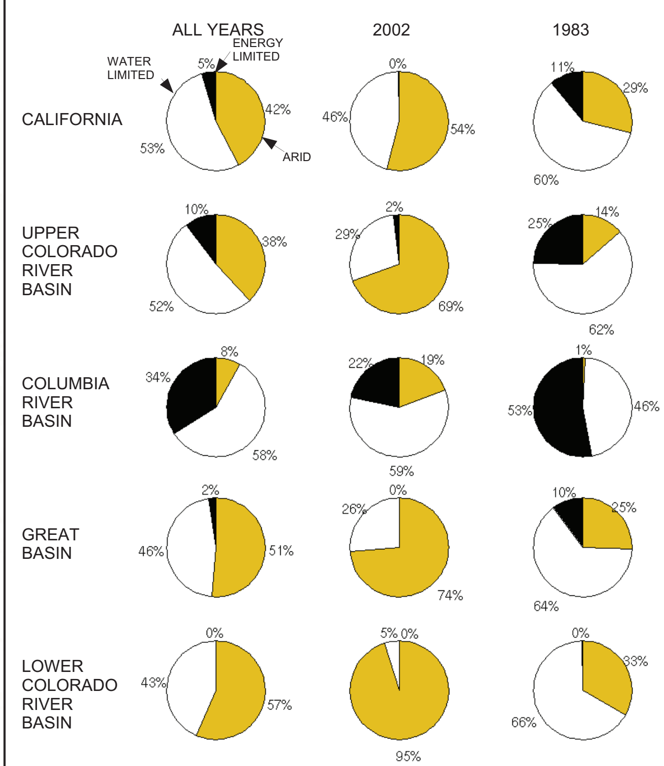
In the energy-limited regions, the effect of drought versus pluvial is evident in AET and PET only during the late spring and summer, because the water budgets can only respond to moisture during the energy-rich warm seasons. In contrast, in the arid regions, moisture availability is a dominant constraint in all seasons and the AET and PET differ all year long from wet to dry years. Only in deep winter do arid landscapes come close to approximating energy-limited in their AET and PET characteristics. However, it is in spring when the AET in arid regions by far most responsive to drought versus pluvial, because this is when water and energy becomes available. Therefore, even in the arid zone, the springtime onset of energy-availability is an important calendar event for determining AET (green water). In a warmer world, will earlier onsets of seasonally warm temperatures (energy-availability) play enough role to change the timing and magnitude of arid zone AET (and its flipside blue water)?

To compare the water budgets of the great river basins in the West, long-term and extreme-year differences between the total areas in the three aridity categories are summarized in Figure 4. On the long term, the Columbia River basin is the most humid region, with the highest percentage of energy-limited areas (34%) and the lowest percentage of arid regions (8%). The Lower Colorado River basin is the most arid region with 57% arid and no energy-limited area. California, in this case the entire state, is largely consumed by water limited (53%) and arid (42%) landscapes with the reminder of about 5% in the energy-limited category. These fractions change dramatically during severe droughts and pluvials. In 2002, areas that are climatologically water-limited became temporarily extremely water-limited (arid) and regions that are climatologically energy-limited became water-limited. During the 1983 pluvial, the opposite occurred and arid and the extent of water-limited regions were sharply reduced. During 2002, drought energy-limited conditions were all but eliminated from all the basins, except the Columbia River basin. The Lower Colorado River basin experienced the largest absolute increase in arid areas (38% of the basin) during the 2002 drought, the Columbia River basin experienced the largest percentage change (138% increase), and California's arid fraction increased to 54% and its energy limited fraction decreased to only 1%. In 1983, the Columbia River Basin experienced the largest absolute increase in energy-limited areas (19% of the basin), the Great Basin presented the highest percentage change (400% increase), and in California it more than doubled to 11% while arid regions dropped to 29% of the total area of the state.

Distribution of Blue and Green Water in the West

Blue water—considered here to be the sum of runoff plus recharge generation at each model grid cell (prior to routing down rivers and aquifers or into various reservoirs)—ranges widely among the western river basins, between 9% of the precipitation supply in the Lower Colorado River basin and over 50% in the Columbia River basin (Figure 5). Green water is the water that evapotranspires (prior to any routing to other

Figure 4.
Average percentages of basin areas in three hydrological conditions: energy-limited AET (black), water-limited AET (white) and extremely water-limited AET or arid (yellow).

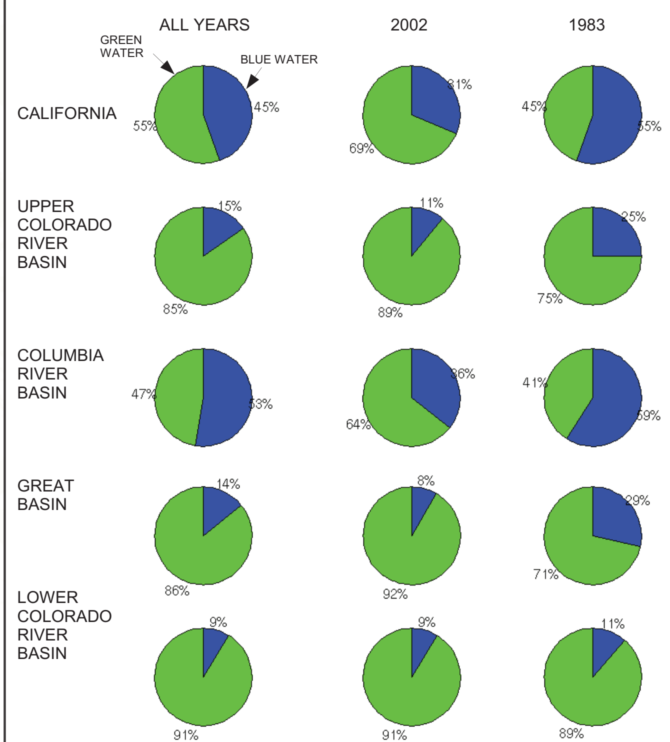


areas) and amounts to the remainder of the precipitation after blue water has been subtracted. The largest sources of blue water in the West are the high-altitude or high-latitude zones of energy-limited AET, so the basins with the largest and wettest energy-limited areas yield the largest fractions of blue water. Blue water is also a higher fraction of the supply of water from precipitation in coastal watersheds along the west coast than in the basins of the interior West. Notably, among the crucial Upper Colorado, California, and Columbia River basins, the (percentage) yields of blue water from the Colorado are significantly less overall than in the other two basins, so that overall the green water fraction from the Upper Colorado River basin: 85% of the total, is more similar to the Great Basin and Lower Colorado Basin deserts than the other major river basins. On average only the Columbia has greater blue water than green water fraction, but during the 1983 pluvial the dominance of the blue water fraction also occured in California. Importantly, the relative fractions of green water increase sharply during drought and decrease during pluvials (Figure 5).

During drought years like 2002, the blue water fractions of the water budgets of the river basins decline, except for the Lower Colorado River basin. The water budget of the Lower Colorado is so arid in the long term that a drought year does not much change the overall (fractional) partitioning between blue and green water yields. The water budget of the Upper Colorado also varies only moderately from the long-term pattern in drought years like 2002. Elsewhere, the drought year 2002 resulted in reductions of the blue-water fractions of about one-third of the long-term blue-water components. These shifts towards smaller fractions of blue water reflect the tendency for runoff and recharge to decline even more in a drought year than does precipitation. The fact that the Colorado River basin (upper and lower) varied less in this regard indicates that runoff effects from droughts in that basin are more proportional (less enhanced relative) to the driving precipitation changes than are runoff effects in other Western basins, largely because so much less of the Colorado runoff comes from energy-limited landscapes. Note, however, that although the Upper Colorado River basin has a higher percentage of energy-limited landscapes than California (Figure 4), on average California has a larger percentage of blue water than the Upper Colorado River basin (Figure 5).

During wet years like 1983, the blue-water fractions of the water budgets increase in all the river basins. The blue-water fractions in the Great Basin increase most (proportionally to long-term fractions) and the blue-water fraction in the Lower Colorado increases least. Notably the blue-water fraction in the Upper Colorado basin increased by about two thirds of its long-term (fractional) contribution. These increases, like the flipside of the drought effects, reflect the tendency for runoff and recharge to increase more, in relative terms, than does precipitation in wet years.

Figure 5.
Average percentages of green and blue water for basins in the western US.



Conclusions

Droughts change the geographic distributions of hydrologic conditions across the West landscape. Arid conditions occupied as little as 15% of the western US landscape in 1983 and swelled to as much as 51% during the 2002 drought. Water supplies, plants and animals adjusted as best they could to drought-pluvial changes—whether of short or long duration--in order to weather the episodic character of historical droughts. The partitioning of whatever precipitation falls between blue water (runoff and recharge) and green water (consumptive use by either evporation or evapotranspiration) also varies with drought and pluvial.

Climate warming, which is already occurring over the West and very likely to be amplified in following decades, may expand extent of arid conditions within the western US. Two separate mechanisms have been suggested: higher evaporation demands in a warmer climate and the potential for more frequent droughts (Seager et al. 2007). The former would be expected to push western water budgets towards larger green-water fractions and smaller blue-water fractions. On the basis of analyses presented here, any persistent reductions in precipitation might be expected to shift water budgets even more towards less overall blue-water generation and more green-water use, because the blue fractions decline more than the precipitation in drought years. Green-water components of the western water budgets are vital parts of the western landscape and ecosystems but represent components that are largely beyond human uses and management. Thus, increases in green-water demands in a warming world must be viewed, to a certain extent, as necessary evils, not to be stopped unless we want very desolate future landscapes indeed.

Shifts in the mean aridity of the west, associated with climate change, even if small compared to the historical year-to-year variations, will be superimposed onto those kinds of variations. That superposition is likely to yield new extremes, both in the areas subjected to unusual aridity and in the severity of drought episodes, so that future drought extremes may be particularly challenging. Because most western landscapes are adapted to accommodate past drought variability that often has been dominated by short-term drought episodes, a gradual but persistent increase in aridity associated with current projections of climate change may be especially important for the redistribution of the species and desertification.

The responses of the western landscapes to long-term droughts or creeping aridity are not likely to be simple, as illustrated by the multivaried changes shown here. More monitoring of soil moisture and other drought-sensitive variables is needed in order to detect changes, and to some extent avoid unpleasant surprises as the western climate changes in response to increasing greenhouse-gas concentrations in the atmosphere. Better monitoring will also provide foundations for proper improvements in hydrologic models and predictions, and for calibration of remote-sensing observations. Such measurements will be of increasing value as this century unfolds and—in the case of soil moisture--have only recently become feasible for widespread deployment. Given the importance and complexity of drought impacts and the possibility of more frequent and perhaps more intense drought in the future, a proactive approach to monitoring is ever more necessary.

Acknowledgments

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References

Falkenmark M and J Rockström. 2004. Balancing Water for Humans and Nature, The New Approach in Ecohydrology. Earthscan. London. 247pp.

Hamlet, A.F. and D.P. Lettenmaier, 1999. Effects of Climate Change on Hydrology and Water Resources in the Columbia River Basin, Am. Water Res. Assoc., 35(6), 1597-1623.

Hamlet, A.F. and D.P. Lettenmaier, 2005. Production of temporally consistent gridded precipitation and temperature fields for the continental US. Journal of Hydrometeorology, 6:330-336.

Hidalgo HG, Cayan DR, Dettinger MD. 2007. Drought – how the western US is transformed from energy-limited to water-limited landscapes. For submission to Journal of Hydrometeorology.

Liang, X., D. P. Lettenmaier, E. F. Wood, and S. J. Burges, 1994.A Simple hydrologically Based Model of Land Surface Water and Energy Fluxes for GSMs, J. Geophys. Res., 99(D7), 14,415-14,428.

Monteith, J. L, 1965: Evaporation and the environment. Symp. Soc. Expl. Biol., 19, 205–234

Nijssen, B., D. P. Lettenmaier, X. Liang, S. W. Wetzel, and E. F. Wood (1997), Streamflow simulation for continental-scale river basins, Water Resour. Res., 33(4), 711–724.

Nijssen, B., G. M. O'Donnell, D. P. Lettenmaier, D. Lohmann, and E. F. Wood (2001), Predicting the discharge of global rivers, J. Clim., 14, 3307–3323.

Penman, H. L, 1948: Natural evaporation from open water, bare soil and grass. Proc. Roy. Soc. London., A193, 129–145.

Rind, D, Goldberg R, Hansen J, Rozenzweig C, and P Ruedy, 1990: Potential evapotranspiration and the likelihood of future drought. J. Geophys. Res., 95, 9983–10004

Seager, R, Ting MF, Held I, Kushnir Y, Lu J, Vecchi G, Huang HP, Harnik N, Leetmaa A, Lau NC, Li CH, Velez J, Naik N. 2007, Model projections of an imminent transition to a more arid climate in southwestern North America. Science 316: 1181-1184.

Shuttleworth WJ. 1993. Evaporation, Chapter 4. In Handbook of Hydrology, Maidment DR. (editor), McGraw-Hill Inc., New York.

Wood A.W., L. R. Leung, V. Sridhar, D. P. Lettenmaier,. 2004. Hydrologic Implications of Dynamical and Statistical Approaches to Downscaling Climate Model Outputs, Climatic Change, 62: 189 – 216

Wood EF, D. Lettenmaier, X Liang, B. Nijssen, and S W Wetzela. 1997. Hydrological modeling of continental-scale basins. Annual Review of Earth and Planetary Sciences. 25: 279-300. doi:10.1146/annurev.earth.25.1.279.

Potential Climate Change Impacts on Colorado River Streamflows During the 21st Century

Brad Udall, Western Water Assessment, University of Colorado

Introduction

The potential impacts of climate change on the Colorado River have been studied for over thirty years with several major studies released in just the past four years. This article summarizes the findings since 2004 from all relevant research on the likely response of the river to climate change. There are four sections in this article with the first portion describing the three major studies on how climate change might affect the runoff of the Colorado River. The second section discusses more general recent studies on potential hydrological changes in the American Southwest under a warmer climate including the new Intergovernmental Panel on Climate Change (IPCC) regional findings. The next-to-last section summarizes the limitations of each of the studies, and the final section draws some general conclusions. Taken together, these studies (Table 1)suggest that projected increases in temperatures due to human-caused climate change will reduce Colorado River runoff by anywhere from 10% to nearly 50% over the coming century.

Recent Colorado River Specific Climate Change Studies

Since 2004 there have been three studies on how climate change might affect runoff in the Colorado River. Common to all three studies are the steps used to approach the problem. First, future temperature and precipitation were obtained from global climate model (GCM) projections. In the second step, the GCM temperature and precipitation, and other climatic variables were used in either statistical relationships (Hoerling and Eischeid) or hydrology models (both Christensen studies) to generate projected Colorado River streamflow in the 21st century. Finally, the Christensen studies used an 'operational' model to convert projected streamflows into reservoir levels, compact deliveries, energy production, and other information. Each study is discussed separately below.

The Effects of Climate Change on the Hydrology and Water Resources of the Colorado River Basin (Christensen, et al., 2004)

Niklas Christensen, Dennis Lettenmaier and several other authors, all of the Department of Civil and Environmental Engineering at the University of Washington, produced this study. The authors used the National Center for Atmospheric Research Parallel Climate Model (PCM) in conjunction with the Variable Infiltration

Table 1

Summary of Studies since 2004 on the Colorado River

Study Name	Type of Study	Results	Comments
Christensen et al., 2004	Colorado River Specific - GCM+Hydrology	-18% runoff by 2040-2069	Only 1 climate model, 1 hydrology model. Superseded by 2006 study.
Christensen and Lettenmaier, 2006	Colorado River Specific - GCM+Hydrology	-6% runoff by 2040-2069	11 climate models, 1 hydrology model.
Hoerling and Eischeid, 2006	Colorado River Specific - GCM+Hydrology	-50% by 2035-2060	18 Climate Models, very simple hydrology hodel.
Milly et al, 2005	Global Climate Model Runoff	Approximately -20% runoff by 2041-60	Study showed 12 GCMs can reproduce historical runoff around globe and by implication project future runoff.
Seager et al, 2006	Global Climate Model Runoff Proxy	Approximately -10% runoff by 2041 to 2060	19 climate models. Modeled area doesn't include entire Green River Basin, also includes large parts of the Southwest not part of Colorado River Basin.
IPCC, 2007	Global Climate Model Precipitation	No number, but precipitation decrease 'likely'	Approximately 20 climate models. Determination is for annual mean precipitation, not runoff. Finding is based on "near unanimity among models with good supporting physical insights."

Capacity (VIC) hydrologic model to simulate runoff and operations on the Colorado River during three future 21st century periods, 2010-2039, 2040-2069, and 2070-2098 (Table 2).

The version of PCM in this study featured coupled atmospheric, ocean, sea ice and land surface components based on approximately 300km grid boxes. At the time, PCM simulations showed less cooling than many other GCMs for the same greenhouse gas emissions. This version of PCM was used in the IPCC's Third Assessment Report 2001and contrasts with the version of PCM and other models that are referenced in IPCC's Fourth Assessment Report released in 2007.

Monthly temperature and precipitation output from PCM was downscaled to 1/8 degree daily data for use by a daily hydrologic simulation model, the Variable Infiltration Capacity (VIC) model. VIC simulates snow accumulation and melt, soil moisture, evapotranspiration, and runoff and baseflow. Runoff and baseflow are routed through a flow network so that streamflow can be calculated. In this study, VIC was calibrated using climate and natural flow data from 1950 to 1989. Calibration runs matched flows at Imperial Dam within 1% of calculated natural flows. At Cisco, near the Colorado-Utah state line, VIC flow was 9% less than calculated natural flow, and at Green River, Utah, VIC was 3% more than calculated natural flow. VIC output was used in a monthly operations model, Colorado River Reservoir Model (CRRM), based roughly on Reclamation's operation model, CRSS.

Model Projections

Three future PCM runs for the 21st century were used. (These "ensemble members" were created by initializing PCM with slightly different atmospheric conditions.) A 50-year control climate run starting in 1995 with no additional greenhouse gas emissions (i.e., with fixed 1995 GHG levels) was also completed. PCM 21st century results averaged over the three runs were compared to the control run, and to historical observed data or calculated natural flow in the historical period.

Due to lags in the climate system, the control run showed warming of about 1ºF (0.5ºC) which is in rough agreement with what many believe to be 'committed warming' should greenhouse gas emissions stop immediately. The three 21st century runs showed average increases of approximately 5.5ºF (3ºC) over the observed average temperature of 50º F (10ºC). In general the warming was concentrated in spring and summer.

Average annual precipitation in the control run was 1% less than historical, and the average of the three 21st-century runs was 3%, 6%, and 3% lower in Periods 1, 2, and 3 respectively. The seasonal precipitation pattern in the control run was very similar to the historical observed, and the 21st century runs showed a similar pattern but with less precipitation in the spring.

April 1 snow water equivalent (SWE) in the control run was only 86% of the observed historical SWE, while SWE was 76%, 71%, and 70% in Periods 1-3, respectively. The reduction in SWE in the control run was attributed to higher spring temperatures, and the 21st century reductions were due to higher temperatures and/or reduced winter and spring precipitation. Southern Colorado suffered the highest reductions and those occurred in Periods 2 and 3.

Runoff was reduced by 10% in the control run, and by 14%, 18% and 17% in periods 1-3, respectively, in the 21st century runs. A spatial analysis of these reductions indicated that a considerable enhancement of evapotranspiration increases occurred in the high elevation areas where a large portion of runoff occurs. Peak runoff advanced from June in the historical data to May in the latter parts of the control and 21st century runs.

Christensen et al., (2004) also reported extensively on how these flows would affect operations as modeled in CRRM. The authors caution that these results strongly depend on initial conditions in the operations model and should not be interpreted as predictions but used instead to find system sensitivities to changes in future flows. Most of the modeling was predicated on constant year 2000 Upper Basin demands to simplify analysis, but a set of runs were done with Upper Basin demands increasing over time.

The authors found that because the Colorado River is nearly at full allocation, reservoir reliability and storage levels were extremely sensitive to inflow reductions. Even small reductions in runoff resulted in significant drops in average reservoir levels. For example, storage in the control run dropped by 7%, and periods 1-3 showed reductions of 36%, 32%, and 40%, respectively, relative to simulated historical conditions. Deliveries from Lake Powell were met 92% of the time in the historical data [1], and 72% in the control run and 59%, 73%, and 77% in periods 1-3, respectively. Variability in the 21st century runs explains some of the other differences. For example, a wet period at the end of Period 2 left system reservoirs at a relatively high level and hence reliability in Period 3 was slightly higher than Period 2 despite roughly similar SWE and runoff.

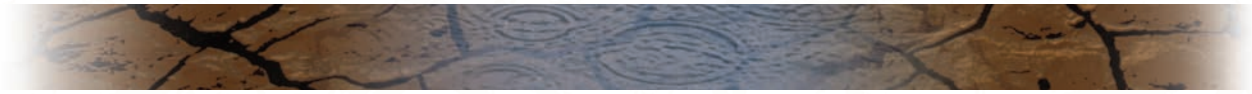


Table 2
Changes in temperature and precipitation provided by NCAR GCM, runoff and snow water equivalent results from VIC hydrology model, and storage, hydropower and spills from CRRM operations model. (from Christensen et al., 2004)

Period	Temperature (°C)	Precipitation	Runoff	April 1 Snow Water Equivalent	Storage
Historical	0.5	354 mm/yr	45 mm/yr		32.3 MAF/yr
Control		-1%	-10%		-7%
2010-39	1.0	-3%	-14%	-2%	-36%
2040-39	1.7	-6%	-18%	-7%	-32%
2070-39	2.0	-3%	-17%	-8%	-40%

Past Peak Water in the Southwest (Hoerling and Eischeid, 2006)

Martin Hoerling and Jon Eischeid of the NOAA Earth System Research Laboratory in Boulder published their findings in December of 2006 in Southwest Hydrology, a magazine (not a peer-reviewed journal) that is part of the National Science Foundation funded effort at the University of Arizona known as Sustainability of Semi-arid Hydrology and Riparian Areas (SAHRA). Hoerling and Eischeid (2006) projected future Colorado River flows by using calculated future Palmer Drought Severity Index (PDSI) values as inputs into a linear regression equation to project future Colorado River flows in a three-step process. PDSI is a frequently used drought metric and is calculated by combining temperature, precipitation, evapotranspiration and soil moisture. The index can vary from -4 (extreme drought) to +4 (extreme wetness).

First, a linear regression equation for the Colorado River basin was created to generate annual flows in MAF at Lee Ferry based on historical data from 1895-1989.

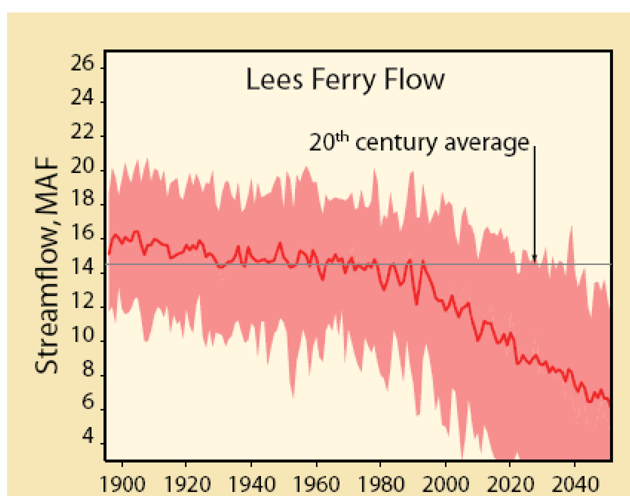
Lee Ferry Annual Flows (in MAF) = 14.5 + 1.69(PDSI)

This regression explains 63% of the variance at Lees Ferry over the 105-year calibration period. The equation explained 85% of the variance in the flows over a verification period from 1990 to 2005. Second, future PDSI values were calculated from 42 different "business as usual" (BAU) climate simulations. Hoerling and Eischeid then calculated the future PDSI using temperature and precipitation data from 42 different climate simulations using 'business as usual' greenhouse gas emissions (A1B) from 18 different coupled atmosphere-land-ocean models completed for the recent IPCC 4th Assessment. Third, the regression model was used to translate calculated future PDSI values into projected future annual streamflow (see Figure 1).

Model Projections

The authors found that annual streamflows in the river over the next twenty-five years would average 10 maf (Figure1), approximately the same as during the recent 1999-2004 drought. From 2035 to 2060 the flows would drop to an average of 7 maf. The individual years vary considerably from these averages with some years being close to the historical mean of 15 maf. For the next twenty years, individual years may still produce normal flows. In some future years the regression equation did generate some streamflows below zero (not shown). Although negative flows are obviously physically impossible, this is a known limitation when regression equations are used outside of their calibration inputs.

Figure 1.
Projected Lee Ferry future flows. Solid line is average of 42 runs, and shaded band shows 10% to 90% range of individual simulations (from Hoerling and Eischeid, 2006)



The authors noted that the climate models show little net change in precipitation over the next century yet significant drought as represented by the modeled PDSI would be a very common occurrence with average PDSI the same as during the 2000-2003 drought (<-3). They suggested that twentieth century droughts were driven by precipitation decreases with enhancement by temperatures but a "near perpetual state of drought will materialize in the coming decades as a consequence of increasing temperature." The models in the study project an average temperature increase of 1.4ºC during 2006-2030, and average warming of 2.8ºC during 2035-2060, compared to 1895-2005.

The authors cautioned that it is unclear if the streamflow-PDSI relationship used in the study is strictly applicable to the substantial changes anticipated in future climate. It should also be noted that the PDSI index was developed for use in the Great Plains and does not account for the different phases of precipitation, snow or rain, and their very different characteristics.

A Multimodel Ensemble Approach to Assessment of Climate Change Impacts on the Hydrology and Water Resources of the Colorado River basin (Christensen and Lettenmaier, 2006)

In late 2006, Niklas Christensen and Dennis Lettenmaier enhanced their 2004 study by using multiple GCM results prepared for the 2007 IPCC Fourth Assessment (AR4). In this study the authors used 11 climate models and two different future emissions scenarios, A2, a relatively high scenario with 2100 CO2 levels of 850 ppm and B1, a relatively low level scenario with 2100 CO2 levels of 550 ppm. (Current CO2 levels are approximately 380 ppm and are increasing at about 1.5 – 2.0 ppm/year.) These two scenarios were selected because they likely bracket any future emissions trajectory and because the GCM output for these scenarios was available from a wide variety of models. As in the 2004 study, for discussion the output was broken into 3 periods: 2010-2039, 2040-2069, and 2070-2099.

Model Projections

For this study the VIC hydrology model was re-calibrated using an additional 10 years of data (1950-99). VIC generated less than 1% underprediction of streamflow at Imperial Dam, and +3% and -9% errors at Green River and Cisco, respectively, based on reconstructed natural flow at these points.

Temperatures increases (ºC) for the B1 runs during periods 1-3, shown as "average (minimum, maximum)," were 1.28 (0.53, 1.83), 2.05 (1.13, 2.99), and 2.74 (1.13, 2.99), respectively, relative to historical observations. For the A2 runs during the same periods, the temperature increases (ºC) by 1.23 (0.63, 1.82), 2.56 (1.61, 3.65), and 4.35 (2.77, 6.06). (Many studies show that temperatures in the next quarter century are tied to existing greenhouse gas concentrations and hence the slightly higher B1 temperature relative to A2 in period 1 is not unusual; generally, changes between emission scenarios show lagged behavior such as reported for periods 2 and 3.) Temperature increases show more warming from mid-summer to early fall, which is consistent with a reduction in soil moisture during these periods.

Annual precipitation percent change from historical for the B1 runs during periods 1-3, shown as "average (minimum, maximum)," were +1% (-8, 11), -1% (-11, 9), -1% (-11, 19), respectively. For the A2 runs and same periods, percent precipitation changes were -1% (-9, 7), -2% (-21, 13) and -2% (-16, 13), respectively. Of critical importance is that October to March average precipitation increases by +5%, +1%, and +2% for B1 and by +6%, +5% and +4% for the A2 scenario. In contrast, the 2004 study had winter precipitation decreases in the single digits. The increases occurred generally at the highest elevations in the Rockies.

April 1 snow water equivalent (SWE) change from historical for the B1 runs, shown as "average (minimum, maximum)," was -15% (-41, 0), -25% (-48, -1), -29% (-53, -18) during for periods 1-3, respectively. For the A2 runs, SWE change was -13% (-36, 1), -21% (-52, 6) and -38% (-66, -15) during the same periods, respectively. The authors believe that SWE decreases are due to increasing temperatures, given especially that winter precipitation increases. SWE reductions are greatest in the low to mid elevation areas. The combination of declining SWE and increasing winter precipitation is indicative of more precipitation occurring as rain.

Mean-annual runoff during periods 1-3 changed from historical by 0% (-23, 17), -7% (-27, 12) and -8% (-30, 29) for the B1 runs, respectively, and by 0% (-16, 14), -6% (-39, 18), and -11% (-37, 11) for the A2 runs during the same periods. These runoff reductions are larger than the precipitation declines but are less than might be supposed given the large April 1 SWE reductions. The runoff declines are believed to be driven by increasing temperatures and higher evapotranspiration but are moderated by increasing winter precipitation.

Table 3
Average ensemble temperature increase, percent changes in precipitation, runoff, and April 1 snow water equivalent all relative to historic 1950-99 modeled base case for both the B1 and A2 emissions scenarios (from Christensen and Lettenmaier, 2006)

Period	Temperature (°C)		Precipitation		Runoff		Snow Water Equivalent	
	B1	A2	B1	A2	B1	A2	B1	A2
2010-39	1.3	1.2	1%	-1%	0%	0%	-15%	-13%
2040-69	2.1	2.6	-1%	-2%	-7%	-6%	-25%	-21%
2070-99	2.7	4.4	-1%	-2%	-8%	-11%	-29%	-38%

Christensen and Lettenmaier also reported results from their operations model, CRRM. CRRM was modified to reflect the Basin States' current proposal with regard to how Lower Basin shortages should be tied to Lake Mead Levels. Hence, the model calculates shortages when necessary to all major Lower Basin entities. They caution that CRRM results reflect many assumptions and non-linear interactions, such as reservoir initial starting conditions and the sequencing of individual annual inflows. In addition, as previously stated, all Colorado River operations models including CRRM fail to address certain critical issues including, for example, Upper Basin curtailments as may be required by the Colorado River Compact during extended drought. Upper Basin demands were fixed at year 2000 levels to simplify analysis yet over time these demands will surely grow. Thus these results should be used only in a comparative sense.

In general, CRRM reservoir levels are higher than reported in the 2004 study, although the authors claim that the results are within the same range of sensitivity. They state that a decrease of 10% in average streamflow is magnified into a 20% change of the same sign in reservoir storage. Similarly, a 20% inflow change results in a 40% storage impact. The authors state that because of the large ratio of storage to inflow in the basin, neither increases in storage nor changes in operating rules will likely change the storage impacts under declining inflows.

Recent Studies Featuring Global Climate Model Projections for the American Southwest

Since 2005 there have been three studies that have analyzed large-scale 21st century GCM projections such as runoff, precipitation and evaporation for the American Southwest. These studies have not utilized smaller scale hydrologic models like the studies described above and in general were not specific to the Colorado River Basin. Nevertheless, conclusions about how the Colorado River will be impacted by climate change can be drawn from these studies.

An important distinction between studies using only global climate model data versus specific Colorado River runoff, is that while GCMs calculate runoff as part of their hydrological cycle at the GCM scale (e.g., 120 mile by 120 mile grid cells), hydrological models like VIC run at much higher resolution, contain far more detailed representations of land surface physics, and are calibrated and verified against streamflow records, which is not typically the case for runoff from GCM internal runoff schemes. On the other hand, the fact that GCM runoff data shows substantial agreement without regional calibration during historical periods with known observations (see Milly et al., below) should provide the reader with considerable confidence that the GCMs are performing relatively well.

Global Pattern of Trends in Streamflow and Water Availability in a Changing Climate (Milly et al., 2005)

In the journal Nature in 2005, USGS scientist Chris Milly and others surveyed runoff proxy information from 12 AR4 GCMs found to be relatively better skilled at reproducing 20th century streamflow trends over large regions (Figure2). The study had both a 'verification' period that used historical data to select the 12 models from 21 potential candidates, and a projection period using SRES A1B scenario that used future runoff generated from the selected models. The American Southwest was not one of the areas used to select the models and hence model fidelity to historical conditions in this region is not known. The study generated runoff projections for the entire globe at the scale of large river basins. In a later not-published addendum to the study, Milly looked specifically at the continental United States and found that based on the same model results greater than 90% of the GCM simulations show future Colorado River basin runoff reductions from approximately 10 to 30% in the period 2041-2060 [2]. (See Table 3.)

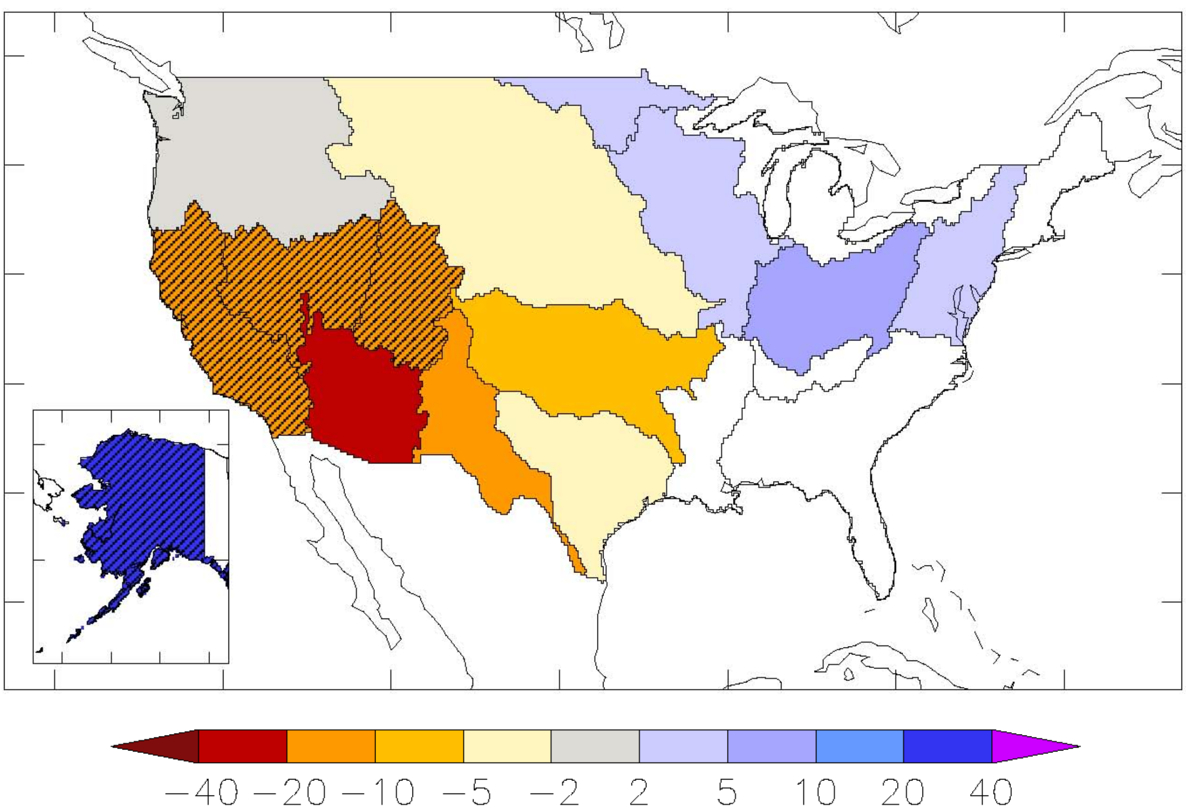
The IPCC AR4 Working Group 1 chapter on climate models (Randall et al., 2007) as well as the AR4 Working Group 2 chapter on freshwater resources (Kundzewicz et al., 2007) both relied on this study. Randall et al. noted that this study was an important scientific advance because it showed that despite the limitations in the hydrologic cycle in the climate models, the models can capture observed changes in 20th century streamflow associated with atmospheric conditions. Further, they say that, "This enhances confidence in the use of these models for future projection."

Model Projections of an Imminent Transition to a More Arid Climate in Southwestern North America, (Seager et al., 2007)

A 2007 study in Science by Columbia University scientist Richard Seager and others, using many of the same GCMs and runoff proxy information as Milly et al., obtained similar conclusions to Milly et al. Unlike Milly et al.'s worldwide focus, Seager's study was specific to an area he termed the 'American Southwest' but was actually far larger than the general use of this term. This area is roughly the SW one-quarter of the United States and includes the entire Lower Basin, but excludes almost all of the Green River and hence is not equivalent to the entire Colorado River basin.

Seager et al., used future GCM projections from 19 AR4 climate models using the A1B emissions scenario compared to 1950-2000 model results. Eighteen of the nineteen models show a drying trend of approximately 10% over the entire area(see figure). Seager et al., focus on the change in future precipitation less future evapora-

Figure 2
Model-Projected Changes in Annual Runoff, 2041-2060 Percentage change relative to 1900-1970 baseline. Any color indicates that >66% of models agree on sign of change; diagonal hatching indicates >90% agreement. After Milly, P.C.D., K.A. Dunne, A.V. Vecchia, Global pattern of trends in streamflow and water availability in a changing climate, Nature, 438, 347-350, 2005.)



tion, a rough proxy for runoff. In support of the modeled runoff declines, Seager et al., (2007) point to theory and studies about how dry areas are expected to get drier and how storm tracks are expected to move northward in the Northern hemisphere. They also discuss recent observational and paleoclimate evidence for support their results. Seager's study was released too late to be included in the IPCC findings, should the IPCC have wanted to include it.

Intergovernmental Panel on Climate Change, 2007

The Fourth Assessment of the Intergovernmental Panel on Climate Change released its report in the spring of 2007 (IPCC, 2007). Chapter 11 from The Physical Science Basis Work Group contains regional climate projections, including North America. This chapter notes that for North America as a whole, the annual mean warming is likely to exceed the global mean warming in most areas. Snow season length and snow depth are very likely to decrease in most of North America, except in the northernmost part of Canada where maximum snow depth is likely to increase. At the coarse horizontal resolution of the climate models, high-altitude terrain is poorly resolved, which likely results in an underestimation of warming associated with snow-albedo feedback at high elevations in western regions.

Specific IPCC findings for the Southwestern USA are that warming will likely be greatest in summer, and that annual mean precipitation is likely to decrease. Projected smaller warming over the Pacific Ocean than over the continent, and amplification and northward displacement of the subtropical anticyclone is likely to induce decrease in annual precipitation in the Southwestern US and northern Mexico. In the context of the report, 'likely' is used to mean a 66% to 90% chance of occurrence. Regional projections are only made for relatively large areas without definite boundaries such as the "Southwestern USA". The IPCC makes regional projections where there is "near unanimity among models with good supporting physical insights." They note that up-to-date coordinated Regional Climate model projections were not available for North America at the time the report was issued.

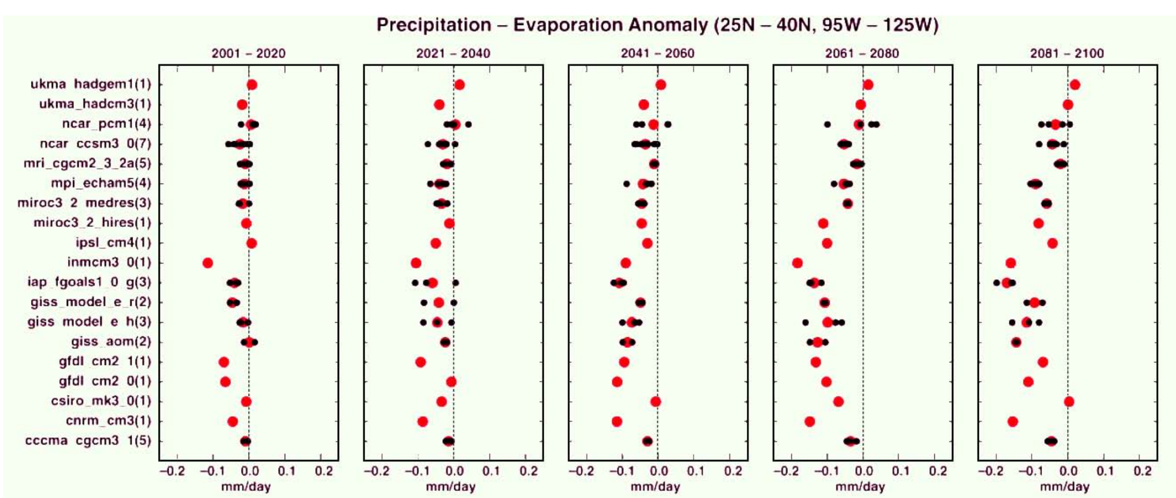
Study Limitations

To put these studies into proper context it is first important to understand the limitations related to GCMs, future applicability of statistical and empirical relationships based on historical data, hydrology model assumptions, and/or operational model assumptions.

In general, GCM temperature projections are considered much more reliable than precipitation. As noted by the IPCC, even with many advances over the years, global climate models still do not adequately resolve precipitation in mountainous areas, in large part due to the large grid boxes which serve to 'flatten' mountains. It is noteworthy, however, that the most recent GCM results for precipitation in the Colorado River basin show somewhat consistent results across models with very little change in average projected annual precipitation relative to historical conditions (Figure 3). Individual

Figure 3

The change in annual mean precipitation minus evaporation (~ runoff) for the American Southwest in twenty-year periods to 2100 calculated relative to model climatologies 1950-2000. Red dots are the ensemble mean and black dots represent individual ensemble members. Only 1 in 19 models has a wet trend and only 3 individual projections out of 49 show a wet trend. (from Seager et al., 2007)



models do, however, show significant variability with the 11 models used in the recent Christensen and Lettenmaier paper showing a range of approximately 90% to 110% of the historical average precipitation at 2050.

Statistical techniques like those used by Hoerling and Eischeid to generate streamflow from precipitation and temperature have been criticized for not being able to address how runoff might change in the future due to changes in evapotranspiration, vegetation, and earlier spring melting. Such changes might substantially alter these relationships and could invalidate results, especially with projections further into the future.

Hydrology models like the VIC model used by the Christensen studies can potentially overcome some of the limitations inherent in the statistical approach by modeling many of the physical processes which control runoff such as snow accumulation and melt, groundwater recharge, and evapotranspiration from plants. In theory as the climate changes, these models should correctly handle new physical conditions. Unfortunately, these models require large amounts of data, much of which is imprecisely known. Furthermore, in order to resolve very complex and sometimes poorly understood relationships, the models may overly simplify important physical processes. For example, the VIC model uses a two-meter subsurface layer to model all interactions with soil moisture and groundwater, despite the fact that surface water/groundwater interactions frequently involve various forms of aquifers with significant storage capacity. Finally, most hydrology models do not have land cover which can respond to changes in climate. Thus, they too might suffer from inaccuracies if the climate changes enough to affect the relationship between land cover and runoff.

Both Christensen studies utilized an operations model (CRRM) created at the University of Washington. While the results of this model is intriguing, it must be noted that the institution of critical management and policy decisions under low flow conditions are not considered. Christensen and co-authors noted these problems and suggested that the operational results only be used in a comparative sense.

Conclusions

All six of these recent studies suggest that by mid- to late-21st Century, decreased runoff is likely to occur in the Colorado River Basin. A few individual climate models in the Christensen 2006 and the Hoerling and Eischeid studies, one out of 19 models in Seager et al. and approximately one out of 12 in Milly et al. do show increases in runoff but these are exceptions to a general finding for decreased runoff.

Unfortunately, the range of declines for the studies using hydrology models by 2050 is rather large, ranging from -5% (Christensen et al), to -50% for Hoerling and Eischeid. Although the Hoerling and Eischeid method can be questioned for using relatively crude techniques, its calibration and verification statistics are quite good. In contrast, the Christensen and Lettenmaier study (2006) is far more sophisticated and shows some results consistent with theories such as increased winter precipitation and increased summer and fall temperatures. On the other hand, Christensen and Lettenmaier has been criticized for understating the impacts of potential future drying on soil moisture and groundwater recharge which could lead to additional runoff declines if modeled.

The range of runoff results from the GCM-only studies is significantly narrower, approximately -10% to -20% by 2050. While it is easy to criticize these studies for using only GCMs, which lack the sophistication seen by many to be necessary to model the complex topography and mid-continental location of the Colorado River basin, their collective findings are important because they suggest that consistent large scale atmospheric processes are to blame for the runoff reductions. This overall paradigm of projected future dryness in an existing desert area also has analogs in other parts world including the Mediterranean. This analog does fall short, however, in explaining how a relatively wet mountainous area like the Rockies close to an existing dry area should respond to future warming.

Research by NOAA, USGS, NRCS, university and other researchers is currently under way to narrow the range of future runoff projections provided by hydrology models. A companion study to look at the range of GCM-only projections, especially models that project either extreme dryness or wetness, is anticipated soon.

Bibliography

Christensen, J.H., B. Hewitson, A. Busuioc, A. Chen, X. Gao, I. Held, R. Jones, R.K. Kolli, W.-T. Kwon, R. Laprise, V. Magaña Rueda, L.Mearns, C.G. Menéndez, J. Räisänen, A. Rinke, A. Sarr and P. Whetton, 2007: Regional Climate Projections. In: Climate Change 2007:The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Christensen, N. S., A. W. Wood, N. Voisin, D. Lettenmaier. 2004. The Effects of Climate Change on the Hydrology and Water Resources of the Colorado River basin. Climate Change 62: 337-363.

Christensen, N. and D.P. Lettenmaier. 2006. A multimodel ensemble approach to assessment of climate change impacts on the hydrology and water resources of the Colorado River basin, Hydrology and Earth System Sciences Discussion, 3:1-44.

Kundzewicz, Z.W., L.J. Mata, N.W. Arnell, P. Döll, P. Kabat, B. Jiménez, K.A. Miller, T. Oki, Z. Sen and I.A. Shiklomanov, 2007: Freshwater resources and their management. Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson, Eds., Cambridge University Press, Cambridge, UK, 173-210.

Hoerling, M. and J. Eischeid. 2006. Past Peak Water in the Southwest. Southwest Hydrology, 6(1).
Milly, P. C. D., K. A. Dunne and A. V. Vecchia. 2005. Global pattern of trends in streamflow and water availability in a changing climate. Nature. 438: 347-350.

Seager, R., M. Ting, I. Held, Y. Kushnir, J. Lu, G. Vecchi, H. Huang, N. Harnik, A. Leetmaa, N. Lau, C. Li, J. Velez, and N. Naik. 2007. Model Projections of an Imminent Transition to a More Arid Climate in Southwestern North America. Science.10:1126.

Note

[1] The historical run used constant 2000 demands unlike the actual historical period where demands have been ramping up over time. Under these conditions some shortages were modeled where in fact no shortages occurred in the historical period.

[2] Enhanced Graphics of the U.S. from the addendum are available at: http://www.gfdl.noaa.gov/~pcm/project/runoff_change.ppt and these graphics are shown below.

Making a Bad Situation Worse: Human-Induced Climate Change and Intensifying Aridity in Southwestern North America

Richard Seager

Lamont Doherty Earth Observatory of Columbia University
Palisades, New York

September 2007

North American hydroclimatic history since the settlement of the West

The Great American Drought was undoubtedly the Dust Bowl of the 1930s. This ranks as one of the worst environmental disasters of the Twentieth Century, anywhere in the world (1). For long it held the record for the largest number of internally displaced persons within the United States - about a third of a million - until, in 2005, Hurricane Katrina achieved in a few weeks what drought in the Plains took years to achieve. The social, economic and political effects of both events were, and will be, long lasting. Population movements during the Dust Bowl facilitated the agricultural and industrial development of the Pacific Rim and began the transformation of the Plains from family to industrial farming and set into motion the system of Federal support for agricultural that we still live with (1).

The reduction of precipitation over the Plains during the 1930s was not the sole cause of Dust Bowl disaster. Years of agricultural expansion during moderately wet times had ripped out drought resistant prairie grasses and planted wheat that was not drought resistant using practices more suited to the humid eastern states. When drought struck crops shriveled and dried exposing bare soil to the winds and leading to soil erosion (1,2). Severe erosion was facilitated by the preponderance of small farms that encouraged farmers to increase cultivated area to try to compensate for reduced yield while the sand that blew from bare fields damaged the land of downwind farmers (3). The result was horrific dust storms that, on top of lost income, made life unbearable for so many of the Plains resident and killed an unknown number of others, especially children, from 'dust pneumonia' (3). We know the complex web of climatic and economic factors that led to the Dust Bowl but, it is not difficult to imagine that in centuries and millennia to come archaeologists digging down through the earth of Oklahoma and Kansas will find the evidence of a lost and short-lived, dispersed and self sucient rural civilization that was felled by drought.

The Dust Bowl drought of the 1930s was just one of six major droughts that have afflicted the West since the expansion of the United States west of the Mississippi (4-7). The drought from the mid 1850s to the mid 1860s was probably the most severe and extensive of these (according to tree ring records) and played its role in the catastrophic decline of bison populations on the Plains as they competed for resources with, and were hunted by, newly nomadic Indians who had arrived after being evicted from a settled life further east by westward-bound pioneers and U.S. Army forces (8, 9). There then followed droughts in the 1870s and early to mid 1890s. The latter caused widespread farm abandonment (10) and led to the Reclamation Act of 1902 and the acceptance that conditions in the drylands were so harsh that settlement and development would have to be on the back of a robust Federal development policy which, once established, has guided the West ever since (11). After the Dust Bowl, drought returned to the Southwest in the 1950s and the most recent drought began in 1998 and, despite some interruptions, we are still living with it. More about that later.

Using climate models to understand the causes of historical North American droughts

Climate modeling efforts in which atmosphere models are forced by known, ship-observed, histories of sea surface temperatures (SSTs, a list of acronyms appears at the end) have recently made clear that all of the these six droughts (including the most recent - at least until 2002), and much of the hydroclimate history of the West, were forced by small variations in tropical SSTs (5,6,12) (Figure 1). The common feature to all is a cold eastern and central equatorial Pacific Ocean - a La Niña-like state (Figure 2). A warm subtropical North Atlantic seems to have also contributed to drought during the 1930s and 1950s (Figures 3 and 4), but not during the three mid to late nineteenth century droughts. The tropical oceans exert this global control in two ways (13).

1. Shifts in SSTs drive shifts in the locations of atmospheric deep convection and the pattern of diabatic heating of the atmosphere. Tropical heating forces atmospheric waves of planetary scale and shifts in the spatial distribution of heating cause shifts in these wave trains creating anomalous rising motion - and more precipitation - in some places and sinking motion - and less precipitation - in other places. During La Niñas the anomalous waves place descending air over the Southwest and Plains and suppress precipitation.

2. Cold equatorial Pacific waters absorb more heat from the atmosphere and cause the tropical atmosphere to

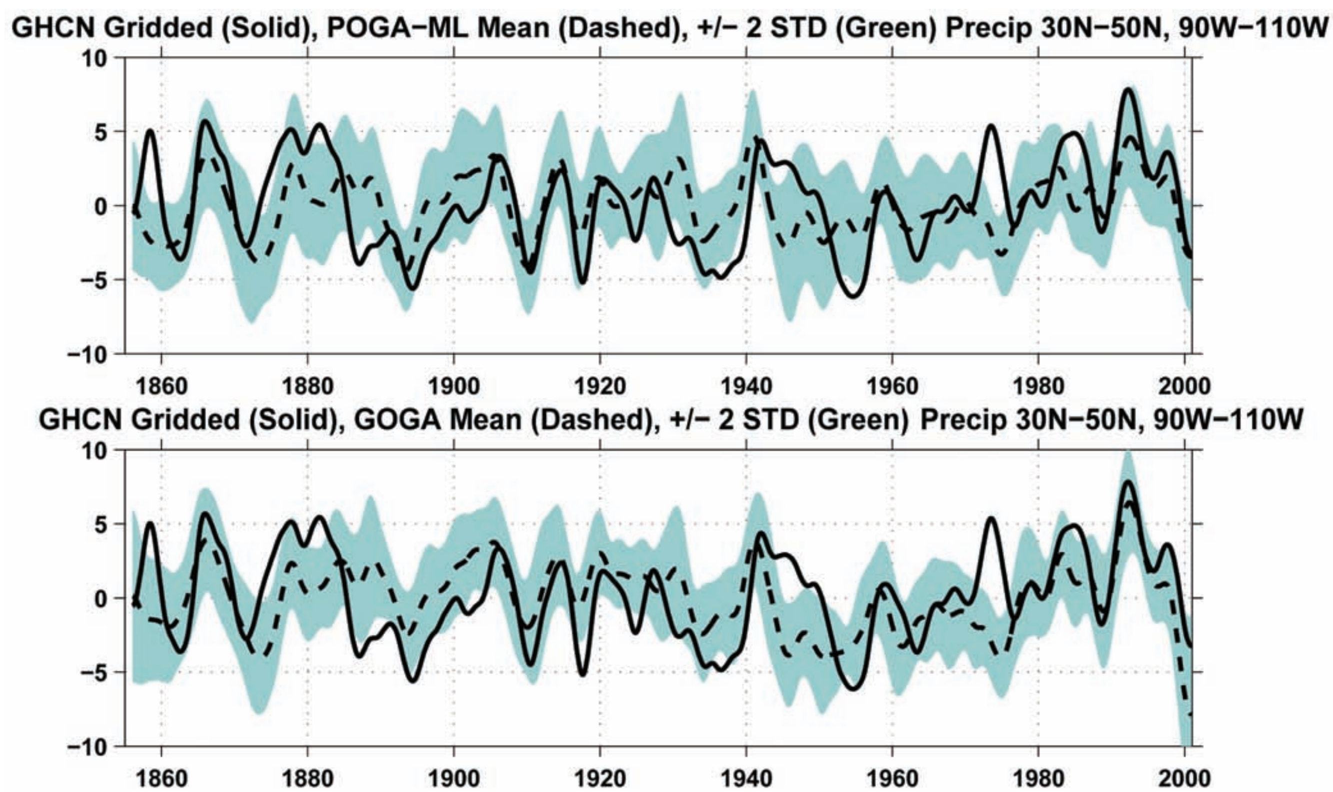
cool. As a result the jet streams shift poleward which impacts the way storms propagate in the atmosphere and, hence, their pattern of momentum transport. Though the dynamics are complex, when the tropical Pacific Ocean and tropical atmosphere are colder than normal, the storms force descending motion in the subtropics and mid-latitudes and suppress precipitation, this time at most longitudes in each hemisphere.

The tropical Pacific SSTs that force the persistent multi-year droughts are thought to arise from natural internal variability of the tropical atmosphere ocean system, essentially a lower frequency version of the El Niño-Southern Oscillation (ENSO). Just why the tropical atmopshere-ocean system caries on these long timescales remains unknown despite abundant theories. However, the analogy to the well studied global response to ENSO means that we have a pretty good understanding of these naturally occurring droughts as a response to tropical ocean forcing while not being sure why the tropical SSTs behave this way. Given the actual history of tropical SSTs, much of the post - 1856 (when ship observations of SST began) hydroclimate history of the West has to a large extent been explained. For example we now know that the wet period in the West that began after the 1976/77 El Niño and continued (with notable respites such as the 1988 drought) until the 1997/98 El Niño was caused by the tropical Pacific Ocean being warmer than normal during these two decades (14). In fact long tree ring records indicate this late 20th Century period to have been among the wettest extended spells in the last millennium. Ironically it was also the period in which the great Southwest population explosion began.

Characteristics and causes of the Medieval North American megadroughts

Severe though the modern droughts were they are dwarfed by a series of 'megadroughts' during Medieval times (roughly 800A.D. to 1500A.D.) that in any one year had intensity comparable to modern droughts but which lasted for decades at a time (14,15). Our best

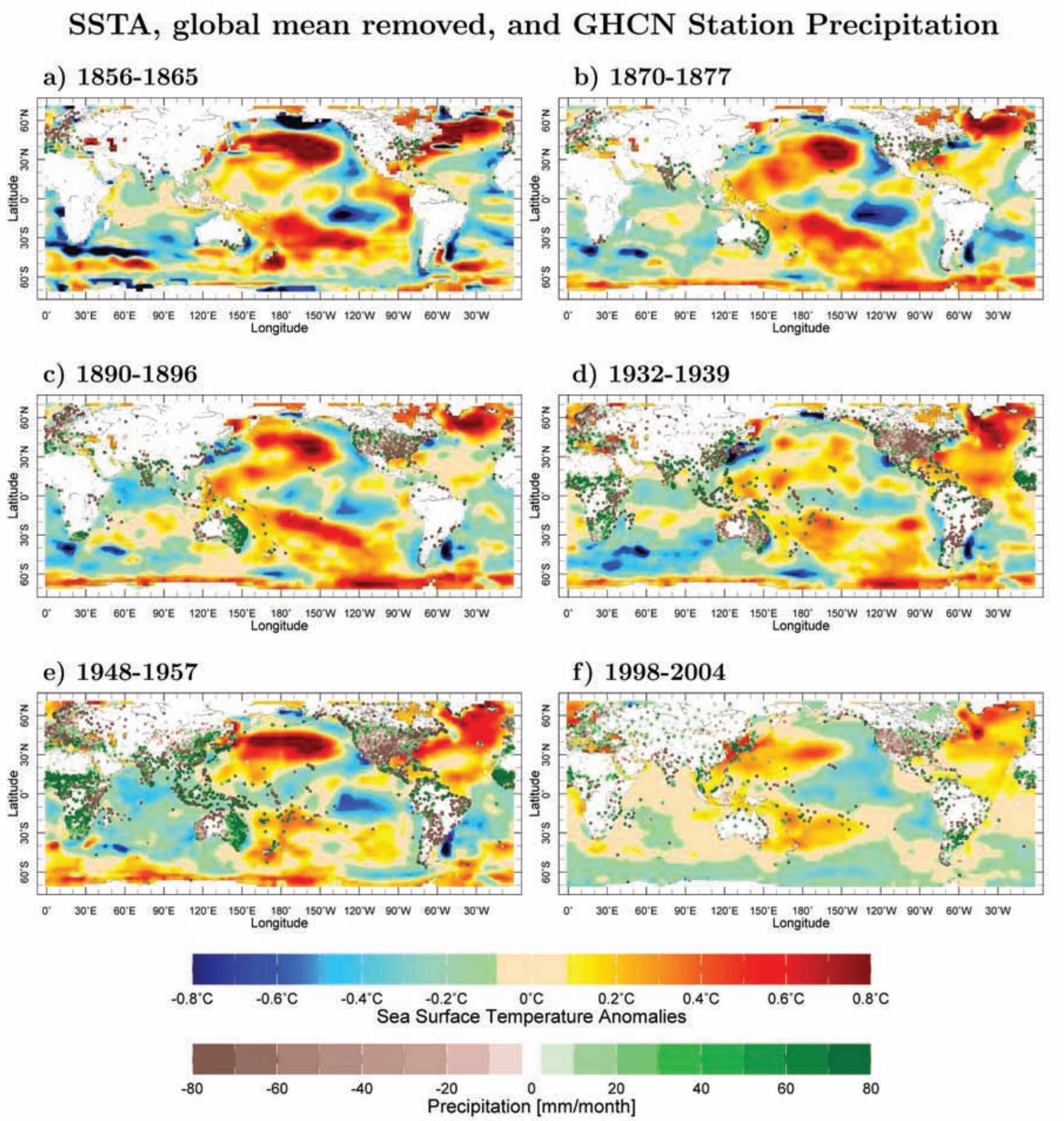
Figure 1.
(a) The precipitation anomaly (mm/month) over the Southwest (120°W–95°W, 25°N– 40°N) for the period 1856 to 2000 from the mean of ensembles of 16 simulations that each began with different atmospheric initial conditions on January 1, 1856 and from gridded station data. (a) is for the case in which sea surface temperatures (SSTs) were imposed in the tropical Pacific Ocean only and calculated elsewhere with an ocean mixed layer model. (b) is for the case where SSTs are specified globally. All data has been six year low-pass filtered. The shading encloses the ensemble members within plus or minus of two standard deviations of the ensemble spread at any time.
From Seager et al. (2005, J. Climate).



analyses of the megadroughts come from long lived tree ring records across North America which show the droughts to have a very similar spatial pattern to modern droughts: dry from the Pacific to the Mississippi and sometimes further east, and from northern Mexico to close to the Canadian border with wet conditions outside of the dry area (15). The pattern similarity suggests that the modern droughts and Medieval megadroughts had similar causes. Further support for a similar cause comes from examining the global spatial pattern of the Medieval hydroclimate using proxy reconstructions from trees, cave speleotherms, lake sediments, etc. which show an overall La Niña like pattern of global hydroclimate (16,17).

Of course we do not have ship observations of SSTs during the Medieval period but we do have records from fossil corals whose geochemistry reflects the tempera-

Figure 2.
The SST anomaly and station precipitation anomaly averaged over all seasons of the six periods of persistent North American drought within the instrumental record. Anomalies are relative to a climatology for the January 1979 to April 2005 period and the global mean anomaly has been removed to emphasize changes in spatial patterns of SST. Units are deg C for SST and mm/month for precipitation.



ture and salinity of the water at the time they were alive. Several fossil corals from the tropical Pacific island of Palmyra cover important segments of the Medieval period (18). From these we can - with a dash of well informed creativity and a certain derring-do - reconstruct maps of tropical Pacific SSTs with annual resolution. Recently we have forced an ensemble of atmosphere model simulations with Palmyra coral-reconstructed tropical Pacific SSTs for the period from 1320A.D to 1462A.D (Figure 5). Modeled soil moisture over North America was verified against the estimates of summer Palmer Drought Severity Index (PDSI) contained within the update of the Cook North American Drought Atlas, a data set of gridded tree ring records with annual resolution (19). For this purpose we used a statistical relation between modern modeled soil moisture variations and modern tree ring reconstructed PDSI and then applied this relation to the modeled Medieval soil moisture to produce a model-estimated Medieval PDSI.

Despite the SSTs being based on corals from a single point and despite coral geochemistry being an imperfect recorder of SSTs and despite the dating uncertainty on the coral (5 years or so), modeled and reconstructed aspects of North American hydroclimate during this period match up surprisingly well (Figure 6). The overall dry conditions are reproduced — due to the fact that the corals indicate prevailing La Niña-like conditions during this century and a half — and many of the year to year variations in tree ring-reconstructed aridity are reproduced as well.

However, while some of the multidecadal swings are captured others are not suggesting that SSTs outside of the Pacific (e.g. the Atlantic) may also have played a role. The model simulated the two megadroughts contained within the period (1360-1400A.D. and 1430-1460A.D.) with both reasonable spatial patterns

Figure 3.

The change in precipitation, averaged over 1932-1939, relative to 1856 to 2005 climatologies for observations (Global Historical Climatology Network (GHCN), top left) and three ensemble mean model simulations. The simulations are with global SST forcing (GOGA, top right), tropical Pacific SST forcing alone and a mixed layer ocean elswhere (POGA-ML, bottom left) and tropical Atlantic SST forcing alone with climatological SSTs elsewhere (TAGA, bottom right). Units are in mm per month.

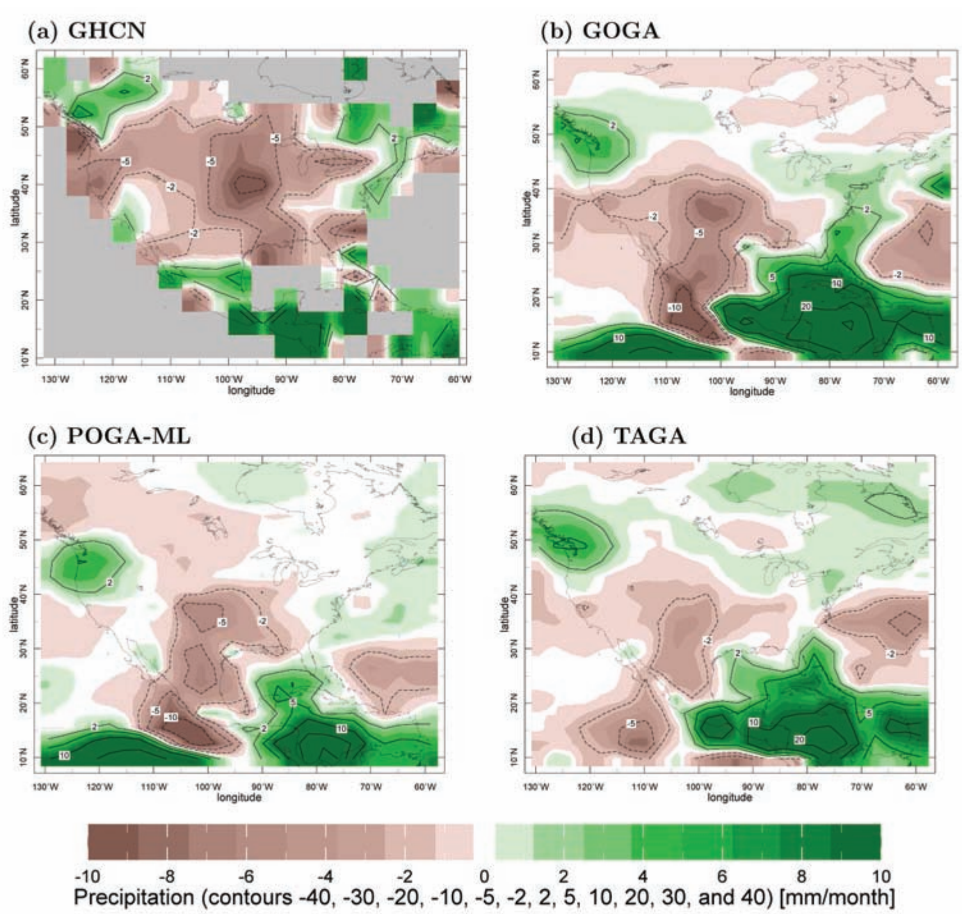
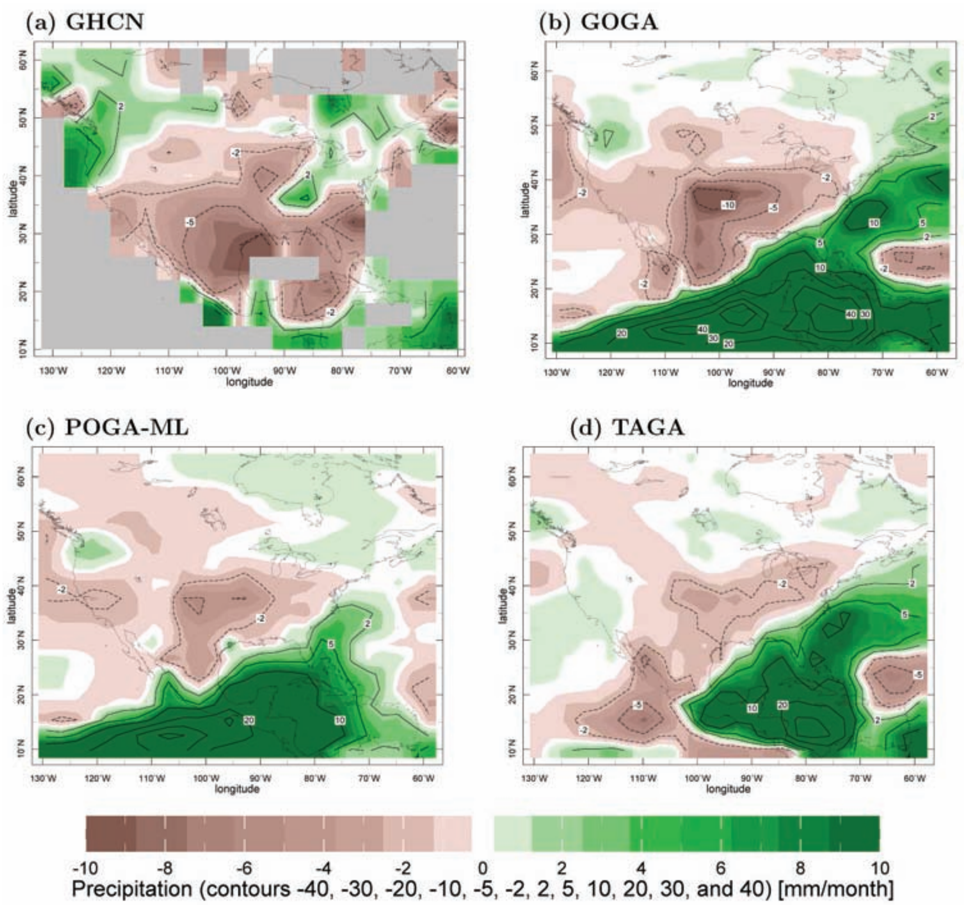


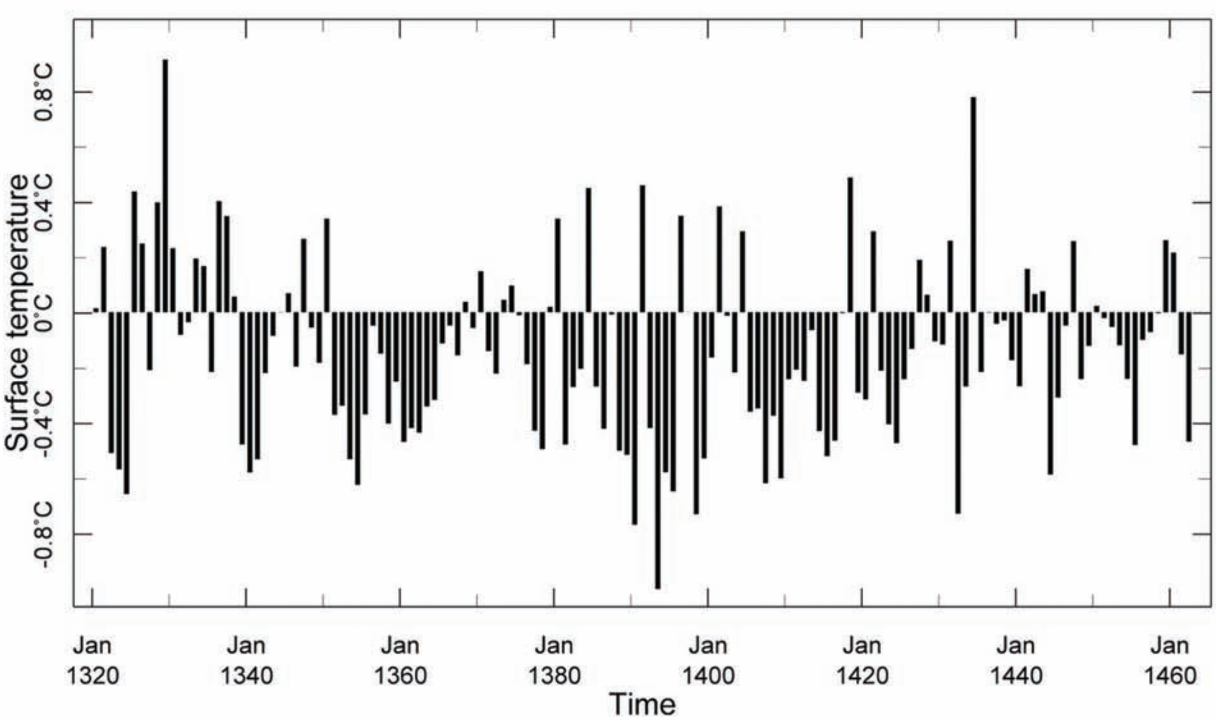
Figure 4.
Same as Figure 3 but for the 1948 to 1957 drought.



and amplitude (Figure 7). These results clearly indicate that a more La Niña-like state of the tropical Pacific during Medieval times played an active role in forcing the megadroughts. The question then turns to what caused the Medieval La Niña-like state? The Sun is thought to have been stronger during the Medieval period than in subsequent centuries which contained the Sporer, Maunder and Dalton minima in solar activity. One theory suggests that stronger radiative forcing can induce a La Niña-like state (20-22). This is because the tropical Pacific Ocean combines a warm pool in the West — a region of the warmest surface waters on the planet overlying a deep warm upper layer — where the surface solar radiation is primarily balanced by radiation and heat export by ocean currents is small and a cold tongue in the east (a strip of cold water formed on the Equator by wind-driven upwelling), where ocean currents export to the north and south about half of the heat the ocean absorbs from the Sun. Consequently, the theory says, a stronger Sun will cause the western equatorial Pacific to warm by more than the east because in the east some of the extra heat is moved poleward. This will strengthen the east to west surface temperature gradient and drive stronger east to west winds increasing upwelling in the east and potentially cooling the waters there - a La Niña-like state.

There are many problems with this theory. Rising greenhouse gases (GHGs) also cause a positive radiative forcing at the ocean's surface so we should see a trend to a more La Niña-like state over the 20th Century. SST observations suggest this is happening (21, 23) but observations of sea level pressure - which has a very close relation to SST - suggest otherwise (24). Further, the theory is based on simulations with the much simplified Zebiak-Cane tropical Pacific atmosphereocean model which was designed for ENSO prediction and neglects many processes that may be important in climate change. Indeed, coupled GCMs (general circulation models, the most complete models we have) respond to positive GHG radiative forcing by essentially warming near-uniformly. In addition there are good theoretical reasons from atmospheric dynamics and

Figure 5.
The coral-reconstructed tropical Pacific SST index (180°– 90°W, 5°S – 5°N) for the 1320-1462 A.D. period minus the 1886-1998 climatology. The reconstruction uses relations between coral geochemistry and tropical Pacific SSTs during the lifetime (1886-1998) of a modern coral to convert coral geochemistry to tropical Pacific SSTs during the lifetimes of a small number of fossil corals (1320-1462 A.D.). This is based entirely on corals from the tropical Pacific island of Palmyra.



thermodynamics for expecting the tropical atmosphere circulation to slow in a warmer atmosphere. This might be expected to reduce ocean upwelling in the east and central equatorial Pacific and prevent a La Niña-like state from emerging (24).

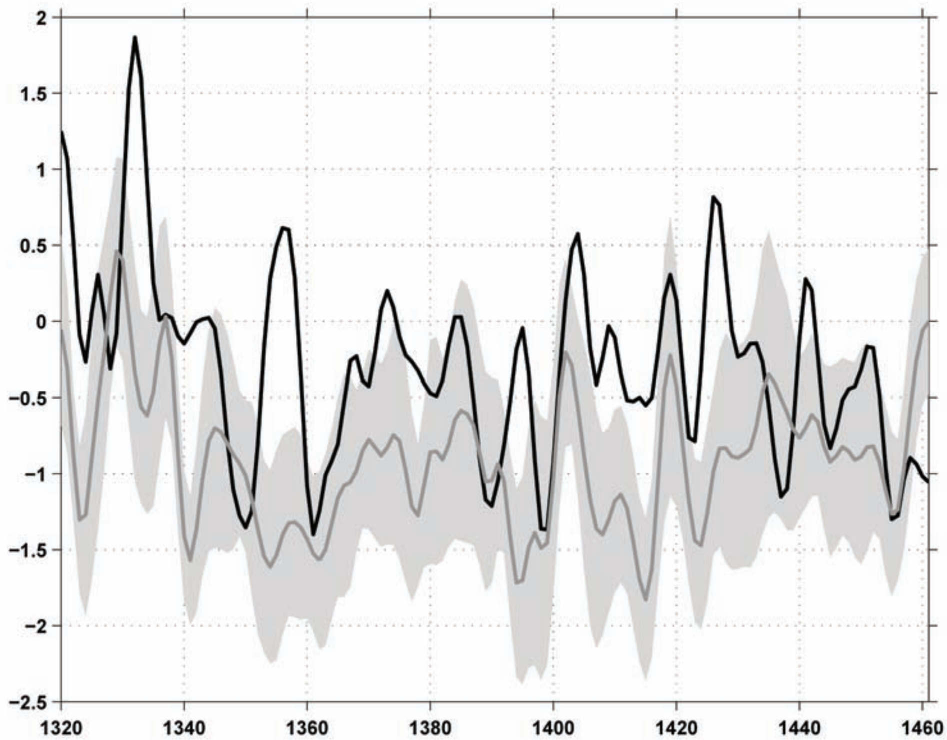
Despite these modeling objections the Medieval association between positive radiative forcing and a dry Southwest is not unique but has occurred throughout the Holocene (25). A La Niña-like response to positive forcing could provide the link. More basic research is needed to answer these questions. In particular the coupled GCMs need to be improved as they currently contain major misrepresentations of tropical Pacific climate that may compromise their simulations of the tropical Pacific climate response to external radiative forcing.

Looking down the slippery slope: the on-going transition to a more arid climate in Southwestern North America

Coupled GCMs may or may not correctly represent the tropical Pacific climate response to rising GHGs but they agree to a remarkable degree that rising global temperatures cause the subtropics to dry (in the sense of reduced precipitation minus evaporation (P –E)), at almost all longitudes and in each hemisphere (Figure 8). This conclusion is based on 19 different models developed by groups around the world and which participated in the IPCC AR4. Southwestern North America is one region to dry but so are the Caribbean and Mediterranean-southern Europe-North Africa- Middle East regions (26). The reduction in P –E is driven by a reduction in P. For southwestern North America P is reduced in winter although E changes little. In summer both P and E are reduced and P – E is changed little. This indicates that reduced P drives down soil moisture with E going down as a consequence (Figure 9).

Models agree on subtropical drying because it is caused by large scale dynamical and thermodynamical processes that we believe models represent well. A warmer atmosphere can hold more moisture and therefore the water vapor transport by the atmosphere intensifies. Currently dry regions - such as the subtropics - are dry because the atmosphere exports moisture from these regions and wet regions - the tropical rain belts and mid-latitudes - are wet becuase the atmosphere converges moisture into these regions. Rising water vapor will intensify these transports and make wet areas wetter and dry areas drier (27). The Southwest is a loser in that process.

Figure 6.
The tree ring-reconstructed PDSI (black) and the ensemble mean model-estimated PDSI (gray) from the coral SST forced simulations. The shading marks the two standard deviation spread of the 16 member model ensemble. All results are 6 year low pass filtered to emphasize longer than interannual timescales. From Seager et al. (2007), submitted to J. Climate).



But climate change is not that simple since the atmospheric circulation also changes. Although the dynamics are not yet fully known, it is a robust result in models that the Hadley Cell which links ascending air - and hence rain - in the tropical rain belts with descending air - and hence aridity - in the subtropics expands its reach poleward in a warmer atmosphere (26). At the same time, and undoubtedly related, the mid-latitude westerly winds and rain-bearing storm tracks move poleward in response to warming (29-31). Both dynamical changes dry the poleward flanks of the subtropical dry zones. Again the Southwest is a loser.

Not only do the models agree that subtropical drying will occur but they also concur that this process should already be underway with the median model transitioning to a permanent state of aridity equivalent to a 1930s or 1950s drought early in the current century. Is there evidence that this change is already underway? Precipitation data with global coverage, which uses satellite observsations, extends back only to 1979 but the 1979 to 2006 precipitation trend does shows quite widespread subtropical drying. It could be that this is related to the shift from an El Niño-like state of the tropical Pacific before 1998 to a more La Niña-like state since then (which could be a natural occurrence) and it could also be affected by trends in the annular modes (modes of internal atmospheric variability that cause meridional displacements of the westerlies and storm tracks). However if we remove from the observed precipitation record the parts that are linearly related to ENSO and annular modes and look at the residual it still shows subtropical drying.

The pattern is similar to that simulated by models as a response to increases in GHGs. However, we need to be cautious as the observed subtropical drying is only statistically significant in some regions and still only marginally so. As such it is still too early to tell with certainty if the projected drying is already occurring.

Conclusions: Or as Mark Twain supposedly said 'Whiskey is for drinking, water is for fighting'

Standing where we are now in 2007 it would be a reasonable conclusion that southwestern North America - and the subtropics in general - will have a drier climate in the future and that transition may already be underway. Or to put it another way, though wet years will still occur, on average they will be drier than prior wet years while the dry years will be drier than prior dry years.

The two decade period of overall wet conditions from 1976 to 1998 is likely to never be repeated as the region faces an intensifying aridity that will simply get worse as the century progresses (barring actual stabilization and then reduction of atmospheric GHGs).

In the model projections increasing aridity occurs for dynamical reasons distinct from those that caused the major historical, persistent droughts, of the last two centuries. It also appears dynamically distinct from the causes of the Medieval period of much elevated aridity which seem also to have been related to La Niña-like patterns of tropical Pacific SSTs. But this difference may be telling us something: The Medieval period was one

Figure 7.
The tree ring-reconstructed PDSI (top), the model-estimated PDSI (middle) and the model soil moisture anomaly both from the model ensemble mean for the 1360-1400 A.D. megadrought and the 1430-1460 A.D. period of the mid-fifteenth century megadrought. From Seager et al. (2007, submitted to J. Climate).

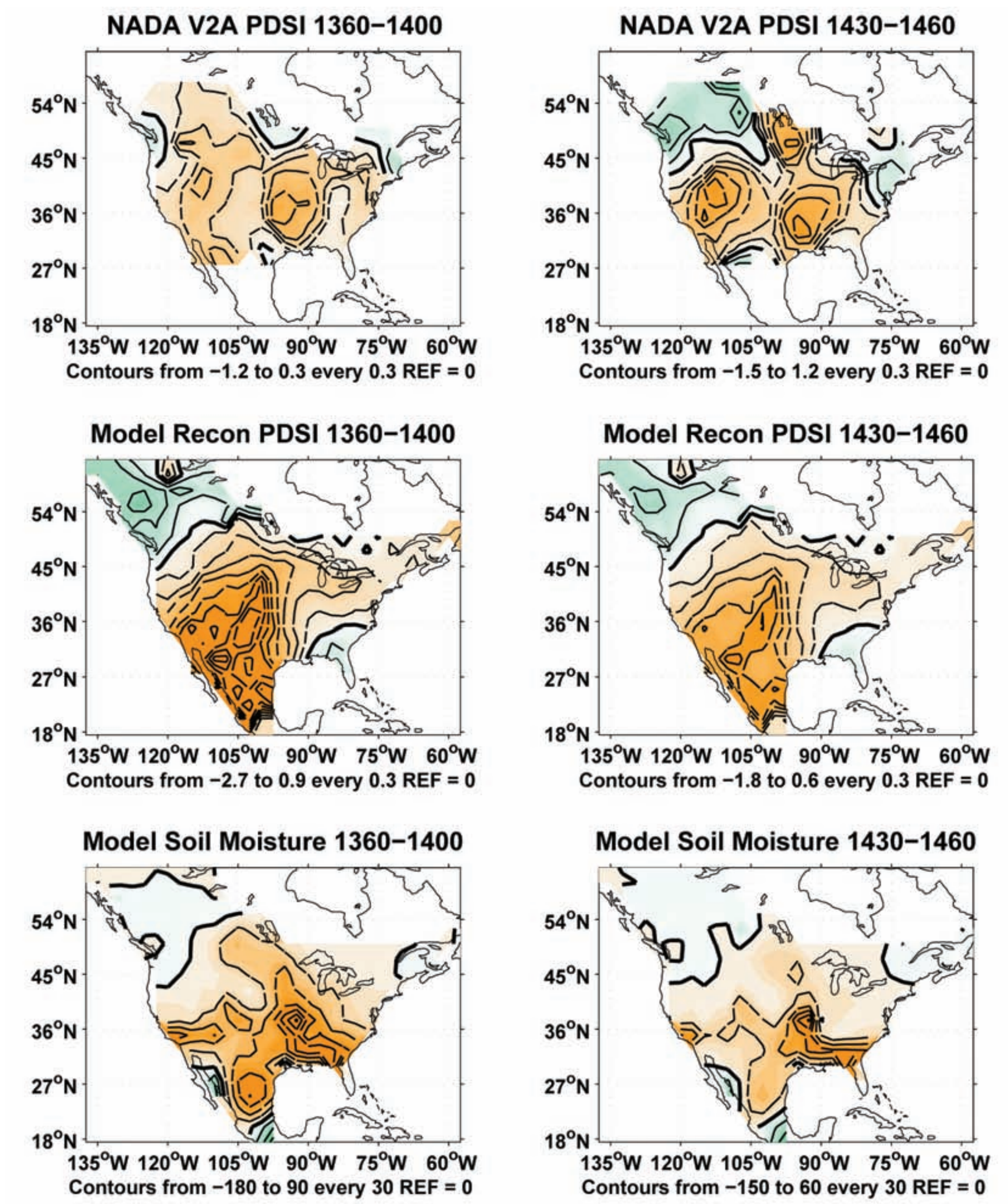
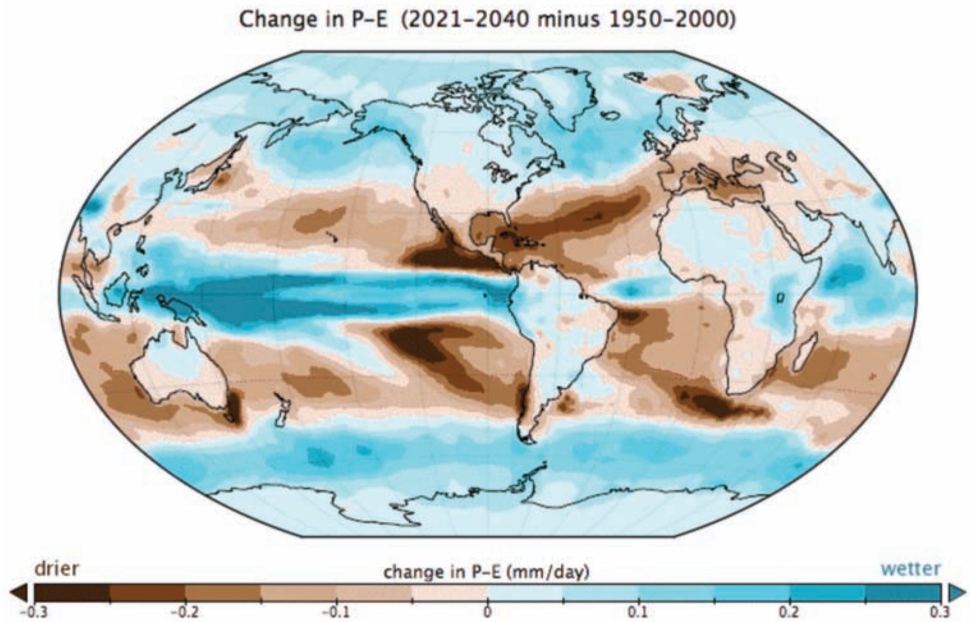


Figure 8.

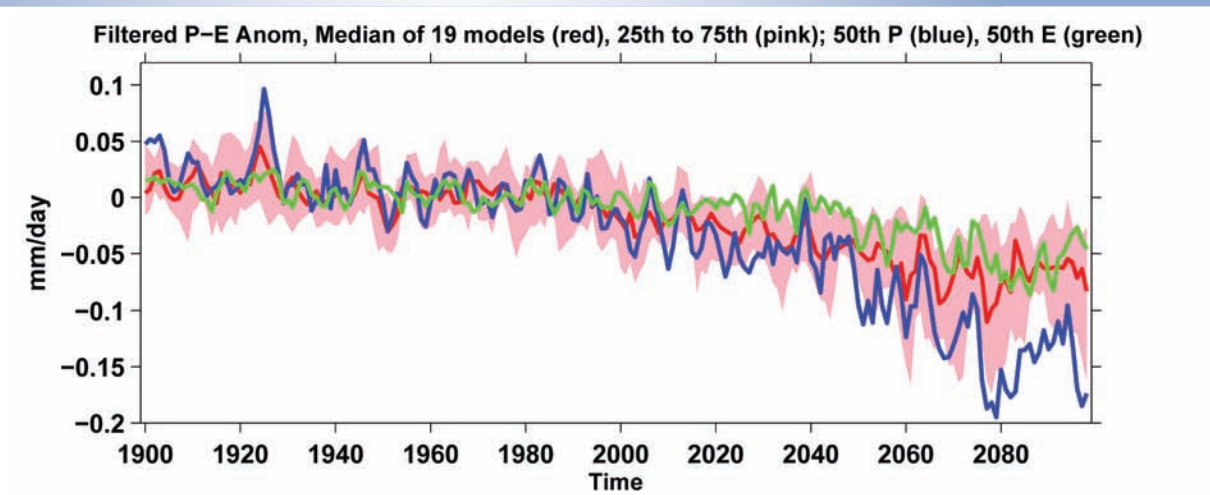
Change in P – E for the 2021-2040 period minus the average over 1950-2000. Results are averaged over simulations of the historical period and projections of the future with 19 different climate models. The future projections follow the middle-of-the-road SResA1B emissions scenario.



of a relatively strong Sun and weak volcanism and what if the associated positive radiative forcing caused the La Niña-like state of the tropical Pacific? According to some theories this could have been so and suggests that GHG forcing could do the same, a response that coupled GCMs miss because of their chronic misrepresentation of the atmosphere-ocean processes that determine the tropical Pacific climate.

Figure 9.

Modeled changes in annual mean precipitation minus evaporation over the American Southwest (125°W – 95°W, 25°N – 40°N, land areas only) averaged over ensemble members for each of the 19 models. The historical period used known and estimated climate forcings and the projections used the SResA1B emissions scenario. Shown are the median (red line) and 25th and 75th percentiles (pink shading) of the P – E distribution amongst the 19 models, and the ensemble medians of P (blue line) and E (green line) for the period common to all models (1900 to 2098). Anomalies for each model are relative to that model's climatology for 1950-2000. Results have been six year low pass Butterworth filtered to emphasize low frequency variability that is of most consequence for water resources. Units are in mm/day. The model ensemble mean P – E in this region is around 0.3 mm/day. From Seager et al. (2007, Science).



If the theories are right and the coupled GCMs wrong then the projected Southwest drying could be a best case scenario with the future actually holding in store a drier climate where general subtropical drying induced by global warming is regionally intensified by a more La Niña-like tropical Pacific.

Either way, there is no way out of this predicament. Subtropical drying in a warmer atmosphere is a robust response of climate models caused by simple thermodynamics and large scale atmosphere dynamics, processes we feel are quite well represented in climate models and not influenced by tricky details of complex small scale processes, such as cloud microphysics. It is hard to think of a reason why the model projections would be wrong. Consequently, since the GHGs we have already put into the atmosphere will warm the planet for decades to come, we can confidently expect the subtropics in general, including the Southwest, to dry. But emissions of GHGs continue and the GHG content of the atmosphere continues to rise putting us on the course to an even drier Southwest climate. Thanks to the Colorado River there is ample water in the Southwest but the problem is with how it is allocated. Currently agriculture takes almost all, even as the urban population grows dramatically. But both agriculture and large houses in deserts communities (because of home heating, air conditioning and reliance on cars for transportation) are energy intensive . Historically the U.S. has been far and away the dominant producer of GHGs. The energy-intensive post 1970s growth of the West has done its fair share to contribute to that but it has come at a price: it is creating a more arid climate in a region where water is already scarce but the demand for it just goes up. Humans are making a bad situation worse and the time is ripe for planning how the Southwest is going to cope with an anthropogenically dried climate.

References and Notes

1. D. Worster, Dust Bowl: The Southern Plains in the 1930s, (Oxford University Press, New York, 1979).
2. T. Egan, The Worst Hard Time, (Houghton-Miin, 2005).
3. Z. H. Hansen and G. D. Libecap, J. Pol. Econ., 112, 665, (2004).
4. F. Fye, D. W. Stahle and E. R. Cook, Bull. Amer. Meteor. Soc., 84, 901, (2003)
5. R. Seager, Y. Kushnir, C. Herweijer, N. Naik, J. Velez. J. Climate, 18, 4068 (2005).
6. C. Herweijer, R. Seager and E. R. Cook, The Holocene, 16, 159, (2006)
7. R. Seager, J. Climate, in press.
8. E. West, The Way the West: essays on the Great Plains, University of New Mexico Press, Albuquerque, 1995.
9. A. C. Isenberg, The Destruction of the Bison, Cambridge University Press, Cambridge, 2000.
10. G. D. Libecap and Z. K. Hansen, J. Econ. Hist., 62, 86 (2002).
11. D. Worster, Rivers of Empire: Water, Aridity and the Growth of the American West, (Oxford University Press, New York, 1985).
12. 13. S. D. Schubert, M. J. Suarez, P. J. Region, R. D. Koster, J. T. Bacmeister, Science, 303, 1855 (2004).
13. R. Seager, N. Harnik, W.A. Robinson, Y. Kushnir, M. Ting, H.-P. Huang and J. Velez, Quart. J. Roy. Meteor. Soc., 118, (2005)
14. H. P. Huang, R. Seager and Y. Kushnir, Clim. Dyn., 24, 721, (2005)
15. E. R. Cook, C. A. Woodhouse, M. Eakin, D. M. Meko and D. W. Stahle, Science, 306, 1015, (2004).
16. C. Herweijer, R. Seager, E. R. Cook and J. Emile-Geay, J. Climate, 20, 1353, (2007).
17. R. Seager, N. Graham, C. Herweijer, A. Gordon, Y. Kushnir and E. R. Cook, Quat. Sci. Rev., in press.
18. K. M. Cobb, C. D. Charles, H. Cheng and R. L. Edwards, Nature, 424, 271, (2003).
19. E. R. Cook and P. Krusic, IGBP PAGES/World Data Center for Paleoclimatology Data Contribution Series, Boulder, CO, 45, (2004).
20. A. C. Clement, R. Seager, M. A. Cane and S. E. Zebiak, J. Climate, 9, 2190, (1996).
21. M. A. Cane, A. C. Clement, A. Kaplan, Y. Kushnir, R. Murtugudde, D. Pozdnyakov, R. Seager and S. E. Zebiak, Science, 275, 957, (1997).
22 . Emile-Geay, M. Cane, R. Seager, A. Kaplan and P. Almasi, Paleoceanogr., 22, doi:10.1029/2006PA001304, (2007).
23. M. A. Cane, Earth Plan. Sci. Lett., 230, 227, (2005).
24. G. A. Vecchi, B. J. Soden, A.T. Wittenberg, I. M. Held, A. Leetmaa and M. J. Harrison, Nature, 441, 73, (2006).
25. Y. Asmerom, V. Polyak, S. Burns and J. Rassmussen, Geology, 35, 1, (2007).
26. R. Seager, M. Ting, I. Held, Y. Kushnir, J. Lu, G. Vecchi, H.-P. Huang, A. Leetmaa. N.-C. lau, C. Li. J. Velez and N. Naik, Science, bf 316, 1181, (2007).
27. I. M. Held, B. J. Soden, J. Climate, 19, 5686 (2006).
28. J. Lu, G. Vecchi and T. Reichler, Geophys. Res. Lett., 34, doi:10.1029/2007GL028443, (2007).
29. J. H. Yin, Geophys. Res. Lett., doi:10.1029/2005GL023684, (2005).
30. P. J. Kushner, I. M. Held and T. L. Delworth, J. Climate, 14, 2238 (2001).
31. L. Bengtsson, K. I. Hodges and E. Roeckner, J. Climate, 19, 3518-3543.

List of acronyms

SST: sea surface temperature.

ENSO: El Niño-Southern Oscillation.

GOGA: global ocean-global atmosphere (used to refer to a global atmosphere model forced by observed SSTs over the global ocean).

POGA-ML: Pacific Ocean-global atmosphere-mixed layer (used to refer to a global atmosphere model forced by observed SSTs in the tropical Pacific alone and coupled to a mixed layer ocean elsewhere).

TAGA: Tropical Atlantic-global atmosphere (used to refer to a global atmosphere model forced by observed tropical Atlantic SSTs and with climatological SSTs elsewhere).

GHCN: The Global Historical Climatology Network compilation of weather station data.

GHGs: greenhouse gases.

PDSI: The Palmer Drought Severity Index.

GCM: general circulation model, commonly used term for a global climate model.

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Correspondence.

Richard Seager, Lamont Doherty Earth Observatory of Columbia University, Palisades, New York 10964; seager@ldeo.columbia.edu

APPENDIX I
DROUGHTS & EMERGENCIES

One of the most frequently asked questions about drought deals with when a drought becomes an emergency. Droughts are rarely emergencies in and of themselves, although impacts of a drought can eventually result in conditions of emergency. Unlike earthquakes, fires, or floods, drought onset is slow, allowing time for water suppliers to implement preparedness and response actions to mitigate reductions in normal supplies. Droughts occur over multi-year periods; there is no universal definition of when a drought begins or ends. The definition of drought is a subjective one, in that it is a function of impacts experienced. Institutionally, there are significant variations in how drought conditions are treated as emergencies under different governmental programs.

The most common perception of an emergency – an immediate condition of disaster or extreme peril – is embodied in California's Emergency Services Act (ESA) (see sidebar). Often used to respond to threats such as a flood or wildfire, the act has also been used to respond to an immediate loss of water supplies, as in the case of the 2001 Klamath Basin drought emergency (described Chapter 1). There has never been a statewide gubernatorial declaration of drought emergency in California pursuant to the ESA. In 1991, the driest single year of the 1987-92 drought, 23 of California's 58 counties declared countywide local states of emergency due to drought. Many of the declarations were prompted by economic impacts associated with loss of dryland cattle range, damage to timber resources and associated wildfire damage, and diminution of water-based recreational and tourism activities – and not by shortages of developed water supplies.

A different approach to declaring drought emergencies – one based on potential near-term economic impacts – is taken by U.S. Department of Agriculture (USDA) in its assistance programs for farmers. In particular, USDA's Farm Services Agency administers an emergency farm loans program that helps farmers and ranchers recover from losses due to drought, floods, other natural disasters, and quarantines. To be eligible for the emergency loans, applicants' operations must be located in a county declared by the President or designated by the Secretary of Agriculture as a disaster area. Table A1 provides examples of some USDA drought emergency designations made for water year 2007. As can be observed from the table, the timeframe USDA uses for making designations is typically brief from a water management viewpoint – often just a few months. This brevity reflects both the importance of seasonal rainfall to activities such as livestock grazing on non-irrigated rangeland and the emergency loan program's intent of providing farmers and ranchers with operational capital. As described in USDA's 2007 fact sheet (USDA, 2007) for its emergency designation and declaration process: *Agricultural-related disasters are quite common. One-half to two-thirds of the counties in the United States have been designated as disaster areas in each of the past several years.*

EMERGENCIES AND DROUGHTS

The California Emergency Services Act, Government Code Sections 8550 et seq, establishes how conditions of emergency are declared and describes the authorities of public agencies to prepare for and respond to emergencies. The state Office of Emergency Services (OES) administers the ESA in coordination with county offices of emergency services. Pursuant to the ESA, a state of emergency may be proclaimed by the Governor or by a city or county. A state of emergency is *the duly proclaimed existence of conditions of disaster or of extreme peril to the safety of persons and property within the state caused by such conditions as air pollution, fire, flood, storm epidemic, riot, drought, sudden and severe energy shortage … which, by reasons of their magnitude, are or are likely to be beyond the control of the services, personnel, equipment, and facilities of any single county, city and county, or city and require the combined forces of a mutual aid region or regions to combat….*

The governing body of a city or county proclaims a local emergency when the conditions of disaster or extreme peril described above exist. The proclamation enables the city or county to use emergency funds, resources, and powers, and to promulgate emergency orders and regulations. (Where a county has declared an emergency, it is not necessary for cities affected by emergency conditions within the county to make an independent declaration of local emergency.) A local proclamation is normally a prerequisite to requesting a gubernatorial proclamation of emergency. The Director of OES may issue a letter of concurrence to a city or county declaration of local emergency. OES concurrence makes financial assistance available for repair or restoration of damaged public property pursuant to the state's Natural Disaster Assistance Act. The Governor proclaims a state of emergency when local resources are insufficient to control the disaster or emergency, typically in response to a local proclamation of emergency. The Governor's proclamation makes mutual aid from other cities and counties and state agencies mandatory, permits suspension of state statutes or regulations, allows for state reimbursement (on a matching basis) of city and county response costs associated with the emergency, and allows property tax relief for damaged private property.

The 2001 Darby Fire in Calaveras County provides an example of typical ESA proclamation of emergency related to water shortage. A September wildfire in the Sierra Nevada foothills burned some 14,000 acres of land and destroyed part of a wooden flume conveying water to the communities of Murphys, the City of Angels, Vallecito, Carson Hill, Douglas Flat, and Six-Mile Village, collectively home to more than 7,500 people. The communities had minimal local water storage capacity. The Calaveras County Office of Emergency Services worked with affected water suppliers on issuance of a notice to area residents to implement extraordinary levels of conservation, limiting water usage to minimum domestic purposes. The County Board of Supervisors proclaimed a local state of emergency, which was followed by a Governor's proclamation of emergency. The Calaveras County Office of Emergency Services, the state Department of Forestry and Fire Protection, and local water agencies immediately began setting up temporary connections/water lines and tanker truck haulage of water, to augment limited supplies available locally. The state-level emergency proclamation allowed OES to provide disaster assistance funding for the temporary measures to restore partial water service, as well as provide funding for eventual permanent repairs, on a 75 percent state/25 percent local cost-sharing basis.

Water Code Sections 350 et seq additionally define the condition of a water shortage emergency, providing that the governing body of a public water supply (whether publicly or privately owned) may declare a water shortage emergency condition in its service area whenever it finds that the ordinary demands and requirements of water consumers cannot be satisfied without depleting the water supply of the distributor to the extent that there would be insufficient water for human consumption, sanitation, and fire protection. Except in the case of an immediate emergency such as a pipeline breakage or pump failure, the declaration must be made at a duly noticed public hearing. This declaration allows the water supplier to adopt regulations covering measures to stretch its supplies, such as mandatory rationing or connection bans.

Special districts often have specific powers in their enabling acts to adopt water rationing and other demand reduction measures. Municipal water districts, for example, have specific authority to adopt a drought ordinance restricting use of water, including the authority to restrict use of water for any purpose other than household use. Additionally, CDPH has the authority to impose terms and conditions on permits for public water systems to assure that sufficient water is available, including the authority to require a supplier to continue a moratorium on new connections adopted pursuant to Water Code sections 350 et seq.

Table A1

Sample USDA Drought Disaster Declarations Made in Water Year 2007

County(ies) declared primary natural disaster areas	Also eligible contiguous counties	Time period disaster experienced
Calaveras	Alpine, Amador, San Joaquin, Stanislaus, Tuolumne	12/06-4/30/07
Colusa	Butte, Glenn, Lake, Sutter, Yolo	12/2/06-3/31/07
Alameda, Nevada	Contra Costa, Placer, San Joaquin, Santa Clara, Sierra, Stanislaus, Yuba	10/1/06-continuing
Madera	Fresno, Mariposa, Merced, Mono, Tuolumne	10/15/06-3/26/07
Kern, Kings, Lake, Mariposa, San Luis Obispo, Santa Barbara	Colusa, Fresno, Glenn, Inyo, Los Angeles, Madera, Mendocino, Merced, Monterey, Napa, San Bernardino, Sonoma, Stanislaus, Tulare, Tuolumne, Ventura, Yolo	10/15/07-continuing
Sacramento	Amador, Contra Costa, El Dorado, Placer, San Joaquin, Solano, Sutter, Yolo	10/1/06-4/30/07
Solano	Contra Costa, Napa, Sacramento, Sonoma, Yolo	12/1/06-4/30/07
Tehama	Butte, Glenn, Mendocino, Plumas, Shasta, Trinity	11/1/06-4/10/07
Inyo, Lassen, Mono, Napa, Placer, Plumas, San Benito, Santa Clara, Shasta, Sierra, Tuolumne, Ventura, Yolo	Alameda, Alpine, Butte, Calaveras, Colusa, El Dorado, Fresno, Kern, Lake, Los Angeles, Madera, Mariposa, Merced, Modoc, Monterey, Nevada, Sacramento, San Bernardino, San Mateo, Santa Barbara, Santa Cruz, Siskiyou, Solano, Sonoma, Stanislaus, Sutter, Tehama, Trinity, Tulare, Yuba	1/1/07-continuing
Monterey	Fresno, Kings, San Benito, San Luis Obispo, Santa Cruz	11/1/06-continuing
Glenn	Butte, Colusa, Lake, Mendocino, Tehama	1/1/07-8/31/07
Riverside	Imperial, Orange, San Bernardino, San Diego	1/1/07-9/6/07
Alpine	Amador, Calaveras, El Dorado, Mono, Tuolumne	1/1/07 – 9/30/07

Only shown are declarations made solely due to drought. USDA made additional declarations for drought in combination with other factors such as freezing temperatures or higher than normal temperatures.

APPENDIX II
DEPARTMENT GRANT PROGRAM FUNDING EXAMPLES

Grant Program Index

Proposition 50 Integrated Regional Water Management Implementation Grants '06-'07. 89

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Proposition 50 Water Use Efficiency Grants '04-'05. 98

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Proposition 13 Groundwater Grants/Loans All Years. 106

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Program/Year Proposition 50 IRWM	Applicant Agency	Implementing Agency	Project Title**	Project Description	Grant/Loan Amount	Total Project
Prop 50 IRWM Implementation Grants/'06-'07**	Mojave Water District	Mojave Water Agency	Regional Water Conservation Program	Fund water conservation programs including retrofit and other incentives proposed by the regional Alliance for Water Awareness and Conservation to reduce consumption by 3,000 af/yr	$250,000.00	$500,000.00
Prop 50 IRWM Implementation Grants/'06-'07	Mojave Water District	Mojave Water Agency	Upper Mojave River Well Field and Water Supply Pipeline Project	Construct wells in the Upper Mojave River floodplain to recharge large volumes of water upstream of extraction field. Up to 40,000 af/yr of water to be pumped for use in areas west of the Mojave River	$21,875,000.00	$42,266,500.00
Prop 50 IRWM Implementation Grants/'06-'07	Mojave Water District	Mojave Water Agency	Oro Grande Wash Recharge Ponds	Construct recharge ponds adjacent to the Oro Grande Wash, a tributary to the Mojave River, with recharge of up to 6,000 af/yr	$2,625,000.00	$5,328,000.00
Prop 50 IRWM Implementation Grants/'06-'07	Sacramento County Consolidated	Sacramento Regional County Sanitation District	Water Recycling Betterment and Expansion Project	Provide the necessary facilities to treat and convey Title 22 tertiary-treated recycled water from SRCSD Water Reclamation Facility (WRF) in Elk Grove to urban irrigation water users in central Sacramento County in-lieu of potable water use.	$2,127,419.00	$49,608,308.00
Prop 50 IRWM Implementation Grants/'06-'07	Sacramento County Consolidated	Sacramento Suburban Water District	Groundwater Well Project	Construct a production well with aquifer storage and recovery (ASR) capabilities plus water treatment and pumping facilities.	$750,000.00	$2,797,617.00
Prop 50 IRWM Implementation Grants/'06-'07	Sacramento County Consolidated	City of Roseville	Woodcreek North Aquifer Storage and Recovery Project	Construct a 1,500 gpm to 3,000 gpm groundwater extraction well with injection capabilities.	$360,000.00	$1,763,000.00
Prop 50 IRWM Implementation Grants/'06-'07	Sacramento County Consolidated	City of Roseville	Roseville Water Treatment Plant	This expansion from the current capacity of 60 MGD to the planned full capacity of 100 MGD is needed to meet peak water demands projected for the service area which is currently converting from agricultural to urban land uses.	$6,030,000.00	$39,000,000.00
Prop 50 IRWM Implementation Grants/'06-'07	Sacramento County Consolidated	Orangevale Water Company and San Juan Water District	Groundwater Production Well Improvement Project	Rehabilitate two existing groundwater extraction wells.	$400,000.00	$1,020,000.00
Prop 50 IRWM Implementation Grants/'06-'07	Sacramento County Consolidated	Citrus Heights Water District	Old Auburn Road Groundwater Production Well	Construct a 1,500 gpm groundwater extraction well.	$600,000.00	$1,480,270.00
Prop 50 IRWM Implementation Grants/'06-'07	Sacramento County Consolidated	Placer County Water Agency	Sunset Industrial Area Groundwater Supply Improvements	Rehabilitate an existing emergency production well and the construction of a new production well.	$750,000.00	$3,000,000.00
Prop 50 IRWM Implementation Grants/'06-'07	Sacramento County Consolidated	City of Lincoln	Lincoln Recycled Water Distribution System Expansion	Convert force mains to recycled water lines, and extending and connecting existing recycled water lines from the City's regional wastewater treatment facility in southwest Lincoln to reclaimed water use locations.	$770,000.00	$4,325,000.00
Prop 50 IRWM Implementation Grants/'06-'07	Greater Los Angeles Metro Consolidated	Central Basin Municipal Water District	Central Basin SWRP	Construct a 12-mile recycled water line from San Jose Creek WRP to distribute up to 16,000 Af/yr of recycled water (13,500 af/yr for City of Vernon refinery) and complete Central Basin Recycled Water System.	$3,530,000.00	$54,151,000.00
Prop 50 IRWM Implementation Grants/'06-'07	Greater Los Angeles Metro Consolidated	West & Central Basin Municipal Water Districts	Large Landscape Conservation	Install 1,950 weather-based irrigation controllers at 500 locations in the watershed to achieve up to 2,000 af/yr in water conservation and 500 af/yr in runoff reduction; Establish a rebate program (2,700 units); Develop 17 demonstration gardens and a public outreach program	$2,100,000.00	$5,291,360.00
Prop 50 IRWM Implementation Grants/'06-'07	Greater Los Angeles Metro Consolidated	Las Virgenes Municipal Water District	Malibu Creek Conservation	Promote indoor and outdoor water conservation by replacing low-efficiency irrigation systems, clothes washers and toilets with more efficient systems.	$426,000.00	$967,360.00
Prop 50 IRWM Implementation Grants/'06-'07	Greater Los Angeles Metro Consolidated	Los Angeles County Flood Control District	Morris Dam Water Supply	Lower the operational pool behind Morris Dam by upgrading the dam's control structures to allow more storm water to be captured for recharge at downstream spreading grounds.	$5,135,634.00	$13,258,175.00
Prop 50 IRWM Implementation Grants/'06-'07	Greater Los Angeles Metro Consolidated	Sanitation Districts of Los Angeles County	Whittier Narrows Water Reclamation Plant UV Disinfection Facilities Project	Address contaminant concentrations in tertiary effluent to allow continued groundwater recharge of 7,000 af/yr (on average) for indirect potable reuse by converting from chloramination to UV disinfection	$2,000,000.00	$7,741,960.00
Prop 50 IRWM Implementation Grants/'06-'07	Pajaro Valley WMA	City of Watsonville PVWMA	Watsonville Recycled Water Treatment Facility	Provide 4,000 AF/Y of a new supply for agricultural irrigation.	$4,425,300.00	$36,453,631.00

Program/Year Cost Proposition 50 IRWM	Applicant Agency	Implementing Agency	Project Title	Project Description	Grant/Loan Amount	Total Project
Prop 50 IRWM Implementation Grants/'06-'07	Pajaro Valley WMA	PVWMA	Coastal Distribution System	Construct pipeline necessary to deliver recycled water and other supplies to the coastal area, ultimately delivering over 18,000 AF/Y.	$7,064,640.00	$44,484,304.00
Prop 50 IRWM Implementation Grants/'06-'07	Bay Area Consolidated***	EBMUD, CCWD	CCWD & EBMUD Regional Intertie	Construct and operate a 100 mgd connection between the Contra Costa Water District (CCWD) and East Bay Municipal Utility District (EBMUD) supply systems.	$1,043,900.00	$8,681,359.00
Prop 50 IRWM Implementation Grants/'06-'07	Bay Area Consolidated***	SFPUC	Bay Area High Efficiency Toilet (HET) Replacement Program	Implement two major incentive programs: one for single-family customers and one for multi-family and commercial customers.	$575,000.00	$1,286,713.86
Prop 50 IRWM Implementation Grants/'06-'07	Bay Area Consolidated***	Redwood City	Redwood City Recycled Water Program	Phase 1 involves construction of recycled water treatment, disinfection, storage, pumping and distribution facilities to provide recycled water to customers in Redwood Shores and the Seaport area.	$972,800.00	$72,371,500.00
Prop 50 IRWM Implementation Grants/'06-'07	Bay Area Consolidated***	City of Palo Alto, City of Mountain View	Mountain View/ Moffett Area Recycled WP	Construct a conveyance pipeline and laterals necessary to serve approximately 122 customers within the Mountain View/Moffett Field Area in the near term.	$972,800.00	$24,766,010.03
Prop 50 IRWM Implementation Grants/'06-'07	Bay Area Consolidated***	EBMUD	Richmond Advanced Recycled Expansion (RARE) Water Project	Design and construct new advanced water recycling facilities to produce high-purity recycled water supply required for the boiler feed water system at Chevron's refinery in Richmond.	$2,127,600.00	$46,834,500.00
Prop 50 IRWM Implementation Grants/'06-'07	Bay Area Consolidated***	North Coast County Water District	Pacifica Recycled Water Project	Deliver 171 AFY of recycled water to six major irrigation customers.	$744,400.00	$7,340,974.00
Prop 50 IRWM Implementation Grants/'06-'07	Bay Area Consolidated***	NMWD	North Marin Recycled Water Project	Construct a 0.5 MGD recycled water facility for landscape irrigation at the Stone Tree golf course in Novato. The project will also deliver water to the NSD and Novato Fire Protection District (NFPD).	$244,550.00	$4,911,456.69
Prop 50 IRWM Implementation Grants/'06-'07	Bay Area Consolidated***	Zone 7	Mocho Groundwater Demin. Plant Project	Construct a 7.7 MGD groundwater demineralization plant.	$733,650.00	$30,378,158.05
Prop 50 IRWM Implementation Grants/'06-'07	Bay Area Consolidated***	MMWD	Bay Water Desalination Project	Construct a desalination plant and associated distribution system improvements, which will be constructed in two phases: 1) construct a 10 MGD facility, and 2) – if needed -- will add a capacity of 5 MGD to the facility.	$366,800.00	$122,104,672.00
Proposition 50 IRWM Subtotal					**$69,000,493.00**	**$632,111,828.63**

** Proposition 50 Implementation Grants were awarded per proposal (group of projects). The projects presented do not make up the entire proposal and the grant amount indicated is based on the grant application, some grant agreements are still pending.
*** This proposal was partially funded so it is unclear how or if the scope of the original proposal will be changed.

2006 Proposition 50 Desalination Grants

Construction Projects

Applicant	Project	Total Cost	Awarded Grant
East Bay Municipal Utility District	Low Energy Application of Desalination (LEAD) Project	$14,640,000	$2,900,000
City of Sand City	Sand City Water Supply Project (SCWSP)	$8,375,000	$2,900,000
Irvine Ranch Water District	Irvine Desalter Project and South Irvine Brine Line	$36,600,000	$300,000
City of Oxnard, Water Division	GREAT Program Desalter - Blending Station No. 1	$20,000,000	$2,900,000
	Total	**$79,615,000**	**$9,000,000**

Pilots and Demonstration Projects

Applicant	Project	Total Cost	Awarded Grant
East Bay Municipal Utility District	Bay Area Regional Desalination Project	$1,898,600	$949,300
Municipal Water District of Orange County	Test Slant Well - Pilot Plant Treatment and Testing Phase	$4,171,226	$1,500,000
Indian Wells Valley Water District	Pilot Testing of Zero-Liquid-Discharge Technologies Using Brackish Groundwater for Inland Desert Communities	$1,189,000	$578,500
Los Angeles Department of Water and Power	Seawater Desalination Pilot Project	$2,877,780	$1,224,300
Board of Water Commissioners of the City of Long Beach	Mitigating Water Quality Effects of Desalinated Seawater	$2,270,000	$1,000,000
Bureau of Reclamation, U.S. Department of Interior	Vertical Tube Evaporator Geothermal Desalination Demonstration Project	$3,693,500	$1,318,605
Affordable Desalination Collaboration	Optimizing Seawater Reverse Osmosis for Affordable Desalination	$2,368,437	$1,000,000
City of Camarillo	City of Camarillo Brackish Water Desalination Pilot Study	$767,744	$383,872
City of Avalon	Catalina Large Diameter Membrane SWRO Energy Reduction Project	$3,637,500	$1,000,000
	Total	**$22,873,787**	**$8,954,577**

Research and Development Projects

Applicant	Project	Total Cost	Awarded Grant
West Basin Municipal Water District	Raw Water Quality Issues Unique to Seawater: Marine Phytoplankton Blooms, their Associated Biotoxins.	$1,245,800	$496,483
Bureau of Reclamation	Development of New Chlorine-Resistant Reverse Osmosis membranes	$2,554,394	$498,679
University of California, Los Angeles	Advanced Monitoring, Optimization, and Control Technologies for High-Efficiency Membrane Desalination	$1,068,256	$500,000
Colorado School of Mines	Novel Hybrid Membrane Desalination Process with Minimal Pretreatment and Concentrate	$1,071,702	$499,957
Sweetwater Authority	Zero Discharge Solar Distillation Research and Development Project	$990,800	$481,500
Lawrence Livermore National Laboratory	Desalination Using Carbon Nanotube Membranes	$749,345	$249,345
Montara Water and Sanitary District	Subsurface Intake Filter Technology Evaluation	$271,213	$135,000
	Total	**$7,951,510**	**$2,860,964**

Feasibility Studies

Applicant	Project	Total Cost	Awarded Grant
Sweetwater Authority	Otay River Basin Brackish Groundwater Desalination Study, Phase 1	$499,000	$242,000
City of Arroyo Grande	South San Luis Obispo County Desalination Funding Study	$90,000	$45,000
San Diego County Water Authority	Feasibility Study of a Regional Concentrate Conveyance Facility in San Diego County	$500,000	$250,000
City of Oxnard, Water Division	Blending Station No. 3 Desalter	$374,000	$187,000
	Total	**$1,463,000**	**$724,000**

2005 Proposition 50 Desalination Grants

Construction Projects

Applicant	Project	Total Cost	Awarded Grant
Marin Municipal Water District	MMWD Desalination Plant	$77,172,043	$3,330,744
Alameda County Water District	Phase 2 Brackish Groundwater Desalination Facility	$10,141,000	$2,800,000
Inland Empire Utilities Agency	Chino II Desalter Expansion	$17,046,000	$2,800,000
	Total	**104,359,043**	**$8,930,744**

Pilots and Demonstration Projects

Applicant	Project	Total Cost	Awarded Grant
City of Santa Cruz	Test Technology Innovations and Optimize Systems in the City of Santa Cruz Desalination Pilot Plant	$3,971,007	$1,982,601
Board of Water Commissioners of the City of Long Beach	Under Ocean Floor Seawater Intake and Discharge Demonstration Project	$5,180,000	$2,000,000
Eastern Municipal Water District	Desalination Recovery Enhancement and Concentrate Management Study	$790,000	$395,000
City of San Diego	San Pasqual Brackish Groundwater Desalination Project - Phase III	$5,090,000	$1,500,000
Coachella Valley Water District	Coachella Valley Groundwater Desalination Project	$1,193,830	$596,915
West Basin Municipal Water District	Demonstration of Integrated Membrane Seawater Desalination Using Single-Pass RO for the Los Angeles Region	$10,213,435	$1,500,000
	Total	**26,438,272**	**$7,974,516**

Research and Development Projects

Applicant	Project	Total Cost	Awarded Grant
Regents of the University of California	UCLA Desalination Research Innovation Project	$2,678,853	$1,000,000
Municipal Water District of Orange County	Horizontal Well Technology Application in Alluvial Marine Aquifers for Ocean Feedwater Supply and Pretreatment	$2,336,903	$1,000,000
Lawrence Livermore National Laboratory	Desalination Using Electrostatic Ion Pumping	$1,991,390	$995,695
Board of Water Commissioners of the City of Long Beach	Ultraviolet Light and Chlorine Dioxide Seawater Pretreatment Systems for Biogrowth Control and Pathogen Inactivation	$2,000,000	$1,000,000
Regents of the University of California	Developing a Tool to Guide State and Local Desalination Planning	$2,597,149	$909,051
Calleguas Municipal Water District	Study of Low Concentration Metals Removal from Brine	$200,000	$100,000
Joint Water Reuse & Desalination Task Force (JWR&DTF)	Joint DWR-JwR&DTF Seawater and Brackish Water Research and Development Program	$2,000,000	$1,000,000
	Total	**13,804,295**	**$6,004,746**

Feasibility Studies

Applicant	Project	Total Cost	Awarded Grant
San Benito County Water District	Pajaro Watershed Groundwater Desalination Feasibility Study	$490,000	$245,000
East Bay Municipal Utility District, on behalf of the Bay Area Regional Desalination Partnership	Bay Area Regional Desalination Project	$499,512	$249,756
City of San Diego	San Diego Formation Brackish G.W. Desalination Project - Phase II	$500,000	$249,700
The Association of Monterey Bay Governments (AMBAG)	Desalination Feasibility Study in the Monterey Bay Region	$211,970	$100,000
West Basin Municipal Water District	Full Scale Seawater Desalination Facility Permitting Requirements in the Santa Monica Bay Area	$590,820	$246,005
San Diego County Water Authority	Feasibility Study for Seawater Desalination at the San Onofre Nuclear Generating Station	$800,000	$250,000
Western Municipal District	Feasibility Study for the Expansion of the Arlington Desalter	$595,218	$249,992
Montara Water and Sanitary District	Feasibility Study of Brackish Water Desalination	$500,000	$250,000
	Total	**4,187,520**	**1,840,453**

Program/Year Proposition 50 Water Use Efficiency	Applicant Agency	Project Title	Grant Amount	Total Project
Prop 50 Water Use Efficiency Grants/06-07	City of Los Angeles	Residential Smart Irrigation Controller Device Installation	$1,650,000	$3,936,120
Prop 50 Water Use Efficiency Grants/06-07	Paradise Irrigation District	WUE Main Replacement Project 1, Bille Road	$602,971	$1,265,332
Prop 50 Water Use Efficiency Grants/06-07	Cucamonga Valley Water District	Fixed Network Large Meter Project	$100,000	$210,676
Prop 50 Water Use Efficiency Grants/06-07	University of California, Davis	Site-specific irrigationto improve WUE & crop quality	$149,276	$149,276
Prop 50 Water Use Efficiency Grants/06-07	Contra Costa Water Dist.	Water Smart Controller Rebate Program	$120,000	$250,229
Prop 50 Water Use Efficiency Grants/06-07	El Dorado Irrigation Dist.	CII/Single & Multi-family ET Controller installation & voucher	$480,450	$960,900
Prop 50 Water Use Efficiency Grants/06-07	Ducks Unlimited	Llano Seco Water Conveyance Structure Replacement Project	$1,740,958	$2,487,083
Prop 50 Water Use Efficiency Grants/06-07	Irvine Ranch Water District	Statewide ET Data Protocol	$156,299	$261,345
Prop 50 Water Use Efficiency Grants/06-07	Metropolitan Water District of Southern California	HECW Program Targeting Water Factor 5.0 or better	$2,000,000	$4,000,000
Prop 50 Water Use Efficiency Grants/06-07	Self-Help Enterprises	Technical Assistance Program	$100,000	$100,000
Prop 50 Water Use Efficiency Grants/06-07	Western Shasta Conservation Dist	Cow Creek Water Use Efficiency	$751,520	$854,000
Prop 50 Water Use Efficiency Grants/06-07	Santa Clara Valley Water District	HET Installation Program for MFDs and CII	$553,750	$1,905,750
Prop 50 Water Use Efficiency Grants/06-07	Municipal Water Dist. Of Orange Co.	Hotel Water Use Reduction Program	$741,564	$2,583,940
Prop 50 Water Use Efficiency Grants/06-07	Municipal Water Dist. Of Orange Co.	Multi-stream, multi-trajectory rotating nozzles	$831,297	$1,377,437
Prop 50 Water Use Efficiency Grants/06-07	Inland Empire Utilities Agency	Large Landscape Water Audit Training & Tech Assistance	$194,476	$386,803
Prop 50 Water Use Efficiency Grants/06-07	Marin Municipal Water Dist.	Regional HECW Rebate Program	$2,981,350	$10,136,640
Prop 50 Water Use Efficiency Grants/06-07	USDA-Agricultural Research Service	Improved prediction of irrigation water use from remote sensing	$149,912	$217,412
Prop 50 Water Use Efficiency Grants/06-07	Central Basin Municipal Water Dist.	High Efficiency Living Program	$1,563,900	$3,259,900
Prop 50 Water Use Efficiency Grants/06-07	Lindsey-Strathmore Irrigation District	High Level Reservoir	$219,008	$243,342
Prop 50 Water Use Efficiency Grants/06-07	Central Basin MWD	Urban City Makeover Program	$113,746	$195,606
Prop 50 Water Use Efficiency Grants/06-07	CUWCC	Making the Connections	$99,649	$246,270

Program/Year Proposition 50 Water Use Efficiency	Applicant Agency	Project Title	Grant Amount	Total Project
Prop 50 Water Use Efficiency Grants/06-07	CUWCC	Reaching Out	$197,320	$549,320
Prop 50 Water Use Efficiency Grants/06-07	CUWCC	Innovations That Work	$147,779	$243,979
Prop 50 Water Use Efficiency Grants/06-07	West Basin MWD	CII Incentive Program	$404,437	$873,000
Prop 50 Water Use Efficiency Grants/06-07	Regional Water Authority	Regional Toilet Replacement Program	$1,120,000	$2,345,000
Prop 50 Water Use Efficiency Grants/06-07	Placer County Water Agency	Foothill Friendly Farms & Landscapes	$199,484	$2,517,397
Prop 50 Water Use Efficiency Grants/06-07	Cal Poly Corporation	Accessible Education for Landscape Irrigation	$98,800	$98,800
Prop 50 Water Use Efficiency Grants/06-07	Paradise Irrigation District	WUE Main Replacement Project 2, Skyway	$522,901	$964,513
Prop 50 Water Use Efficiency Grants/06-07	California State University, Fresno Foundation	WATERIGHT website	$42,900	$42,900
Prop 50 Water Use Efficiency Grants/06-07	Placer County Water Agency	Newcastle Canal & Upper Banvard Canal Seepage Reduction	$65,703	$657,030
Prop 50 Water Use Efficiency Grants/06-07	San Diego Water Authority	Water Budget Web Enabling	$200,000	$254,642
Prop 50 Water Use Efficiency Grants/06-07	Glenn-Colusa Irrigation District	Water Conservation and Management Project	$2,383,000	$2,733,160
Prop 50 Water Use Efficiency Grants/06-07	City of Woodland	City Parks Irrigation Improvement Project	$996,200	$2,999,700
Prop 50 Water Use Efficiency Grants/06-07	Cachuma RCD	Mobile Irrigation Lab	$188,357	$249,717
Prop 50 Water Use Efficiency Grants/06-07	Reclamation District 1500	Joint Sutter Basin Irrigation Recycling Project	$182,720	$197,720
Prop 50 Water Use Efficiency Grants/06-07	Ag Water Management Council	Online AWMP application	$91,875	$91,875
Prop 50 Water Use Efficiency Grants/06-07	East Bay MUD	Automatic Meter Readings	$248,600	$621,500
Prop 50 Water Use Efficiency Grants/06-07	East Bay MUD	Food Service Water & Energy Efficiency One Stop	$226,188	$452,375
Prop 50 Water Use Efficiency Grants/06-07	Cal Poly Corporation	Accessible Education for Ag Irrigation	$97,300	$97,300
Prop 50 Water Use Efficiency Grants/06-07	Pacific Institute	Urban WUE Scenarios w/ and w/out climate change, to 2050	$93,461	$93,461
Prop 50 Water Use Efficiency Grants/06-07	Central Basin Municipal Water District	Conservation Outreach Targeting Multicultural Communities	$100,000	$170,000
Prop 50 Water Use Efficiency Grants/06-07	Cal Poly Corporation	Tech Assistance to Areas Serving Disadvanted Communites	$194,300	$194,300

Program/Year Proposition 50 Water Use Efficiency	Applicant Agency	Project Title	Grant Amount	Total Project
Prop 50 Water Use Efficiency Grants/06-07	City of Maywood	Helping Our People and Environment (HOPE)	$664,500	$1,159,500
Prop 50 Water Use Efficiency Grants/06-07	University of California, Davis	Evaluating ET of Wine Grapes	$149,148	$149,148
Prop 50 Water Use Efficiency Grants/06-07	Municipal Water District of Orange County	Assessment of MWDOC Water Loss Management Program	$100,000	$218,600
Prop 50 Water Use Efficiency Grants/06-07	Imperial Irrigation District	Lateral Heading Automation Program	$180,077	$1,800,771
Prop 50 Water Use Efficiency Grants/06-07	San Francisco PUC	HET Low-income direct install program	$200,000	$505,627
Prop 50 Water Use Efficiency Grants/06-07	University of California, Davis	Survey of Wine grape Irrigation Practices	$99,750	$99,750
Prop 50 Water Use Efficiency Grants/06-07	California State University, Fresno Foundation	Water Efficient irrigation Systems & Mgmt Education	$100,000	$100,000
Prop 50 Water Use Efficiency Grants/06-07	Cachuma RCD	Landscape Evaluations and Rebates using Mobile Lab	$200,000	$311,063
Prop 50 Water Use Efficiency Grants/06-07	California State University Monterey Bay	Development of the Viticultural Information System (VITIS)	$189,500	$189,500
Prop 50 Water Use Efficiency Grants/06-07	California Avocado Commission	Study at Groves for Irrig. Regulated by ET Controllers	$75,000	$95,000
Prop 50 Water Use Efficiency Grants/06-07	Orland Unit Water Users Association	Orland Project Regulating Reservoir Construction	$2,490,895	$2,962,523
Prop 50 Water Use Efficiency Grants/06-07	Consolidated Irrigation District	Canal Modernization	$200,000	$282,790
Prop 50 Water Use Efficiency Grants/06-07	University of California	Refined Crop Coefficients to Improve Planning & Management	$148,423	$218,236
Prop 50 Water Use Efficiency Grants/06-07	Lawrence Livermore Berkeley National Laboratory	Water Conservation Impact on Peak & Off-Peak Electricity Usage	$150,000	$165,000
Prop 50 Water Use Efficiency Grants/06-07	Long Beach Water Department	Water-Use Accountability in Large Multi-Family Developments	$26,500	$26,500
Prop 50 Water Use Efficiency Grants/06-07 Subtotal			**$28,075,244**	**$59,759,758**
		Totals	**$93,201,666**	**$199,591,801**

Program/Year Proposition 50 Water Use Efficiency	Applicant Agency	Project Title	Grant Amount	Total Project
Prop 50 Water Use Efficiency Grants/04-05	Western Canal Water District	Canal Elevation Structure Replacement	$104,929	$419,714
Prop 50 Water Use Efficiency Grants/04-05	USDA WMRL	Improved Water Use Efficiency for Vegetables	$248,000	$508,000
Prop 50 Water Use Efficiency Grants/04-05	Deer Creek Irrigation District	Deer Creek Agricutural Water Use Efficiency Program Long-Term Sytem Improvements Feasibility Investigation	$172,850	$172,850
Prop 50 Water Use Efficiency Grants/04-05	Orland Unit Water Users Association	Orland Project Regulating Reservoir Feasibility Investigation	$168,153	$176,153
Prop 50 Water Use Efficiency Grants/04-05	University of California	Monitoring Wetting Front Advance Rate for Irrigation Management in Flood Irrigation Alfalfa Production System	$97,110	$97,110
Prop 50 Water Use Efficiency Grants/04-05	Plant Science University of California, Davis	Benefits and Costs of Deficit Irrigation in Alfalfa	$632,000	$702,000
Prop 50 Water Use Efficiency Grants/04-05	Yolo County RCD	Irrigation improvement-Mobile Lab Prog.	$100,500	$114,500
Prop 50 Water Use Efficiency Grants/04-05	Reclamation District 108	Reclamation/BWMP Cooperative Water Measurement Study	$318,803	$479,803
Prop 50 Water Use Efficiency Grants/04-05	Yolo County Flood Control & Water Conservation District	Flow Monitoring Network	$272,000	$599,144
Prop 50 Water Use Efficiency Grants/04-05	Lost Hills Water District	Service Area 7N Canal Lining Project	$245,760	$307,200
Prop 50 Water Use Efficiency Grants/04-05	Lost Hills Water District	Service Area 4 Canal Lining Project	$559,140	$745,520
Prop 50 Water Use Efficiency Grants/04-05	Glenn-Colusa Irrigation District	Glenn-Colusa Irrigation District Regulatory Reservoirs Feasibility Study	$257,000	$308,400
Prop 50 Water Use Efficiency Grants/04-05	Stevinson Water District	Lateral Canal Piping Project	$896,000	$1,003,200
Prop 50 Water Use Efficiency Grants/04-05	Anderson-Cottonwood Irrigation District	ACID Churn Creek Lateral System Improvements Project-Feasibility Study	$144,000	$149,000
Prop 50 Water Use Efficiency Grants/04-05	Modesto Irrigation District	Water Conservation Ditch and Pipeline Replacement	$500,000	$1,029,400
Prop 50 Water Use Efficiency Grants/04-05	Central Basin Municipal Water District	Commercial Landscape Wireless Valve End Use Management Research Project	$164,052	$302,052
Prop 50 Water Use Efficiency Grants/04-05	UC Regents	Improvement of CIMIS ETo Maps	$214,919	$214,919
Prop 50 Water Use Efficiency Grants/04-05	Clovis Botanical Garden Committee	Clovis Botanical Garden Expansion	$72,362	$96,425
Prop 50 Water Use Efficiency Grants/04-05	Irvine Ranch Water District	CA Single Family Residential Water Use Efficiency Study	$761,668	$996,668
Prop 50 Water Use Efficiency Grants/04-05	City of San Diego	Recirculating Hot Water Systems: Residential Survey and Feasibility Study	$30,100	$30,100
Prop 50 Water Use Efficiency Grants/04-05	Santa Clara Valley Water District	Water Efficiency Demonstration Garden	$146,000	$194,173

Program/Year Proposition 50 Water Use Efficiency	Applicant Agency	Project Title	Grant Amount	Total Project
Prop 50 Water Use Efficiency Grants/04-05	Alameda Point Collaborative	Ploughshares Demonstration Garden	$193,460	$193,460
Prop 50 Water Use Efficiency Grants/04-05	Alameda Point Collaborative	Water Efficient Landscaping	$308,000	$792,000
Prop 50 Water Use Efficiency Grants/04-05	California Urban Water Conservation Council (EBMUD)	California WaterStar Initiative: Water Efficiency Product Rating and Labeling	$217,000	$325,600
Prop 50 Water Use Efficiency Grants/04-05	California State University, Fresno Foundation	Irrigation System Audits by Students	$159,392	$159,392
Prop 50 Water Use Efficiency Grants/04-05	South Yuba River Citizens League	"The Great Water Mystery" School Assemblies and School Water Audit	$51,717	$105,435
Prop 50 Water Use Efficiency Grants/04-05	Metropolitan Water District of Southern California	Online/Web-Based Irrigation Efficency Training	$77,500	$155,000
Prop 50 Water Use Efficiency Grants/04-05	California Urban Water Conservation Council	Urban Water Efficiency Technical Assistance Program	$506,913	$666,577
Prop 50 Water Use Efficiency Grants/04-05	California Urban Water Conservation Council	Smart From the Start	$104,496	$126,079
Prop 50 Water Use Efficiency Grants/04-05	East Bay Municipal Utility District	New Business Plan Review Program For Water Use Efficiency	$50,000	$200,000
Prop 50 Water Use Efficiency Grants/04-05	East Bay Municipal Utility District	Multi-Family Submeter Pilot Study	$150,000	$300,000
Prop 50 Water Use Efficiency Grants/04-05	Water Education Foundation	Project Wet (Urban Focus)	$79,599	$79,599
Prop 50 Water Use Efficiency Grants/04-05	Stockton East Water District	Water Awareness Exhibit Refurbishment for the Children's Museum of Stockton	$54,000	$60,000
Prop 50 Water Use Efficiency Grants/04-05	Pacific Institute for Studies in Development, Environment, and Security	Development of a Water Use Efficiency Implementation Cost and Cost Effectiveness Model	$142,385	$142,385
Prop 50 Water Use Efficiency Grants/04-05	Lawrence Livermore Berkeley National Laboratory	Determining Waste of Water and Energy in Residential Hot Water Distribution Systems	$500,000	$1,043,725
Prop 50 Water Use Efficiency Grants/04-05	Deer Creek Irrigation District	Deer Creek Agricultural Water Use Efficiency Program Near-Term System Improvements Project	$453,035	$453,035
Prop 50 Water Use Efficiency Grants/04-05	Patterson Irrigation District - Orange Avenue	Decision Support for Implementation and Evaluation of Agricutural Water Reuse Best Management Practices to Improve District-Level Irrigation Efficiency	$705,580	$1,365,550
Prop 50 Water Use Efficiency Grants/04-05	Irrigation Training and Research Center	Technical Assistance to Irrigation Districts	$387,500	$515,300
Prop 50 Water Use Efficiency Grants/04-05	California State University Monterey Bay - Foundation	Characterizing Spatiotemporal Variations in Canopy Density, Soils, Climate, and Vineyard Water Balances	$118,590	$118,590
Prop 50 Water Use Efficiency Grants/04-05	University of California, Davis. Agronomy/Range Science	Water Use Efficiency in Sacramento Valley Rice Cultivation	$428,000	$459,360
Prop 50 Water Use Efficiency Grants/04-05	Agricultural Water Management Council	Agricultural Water Management Informational Resources Directory	$62,680	$62,680

Program/Year Proposition 50 Water Use Efficiency	Applicant Agency	Project Title	Grant Amount	Total Project
Prop 50 Water Use Efficiency Grants/04-05	University of California, Davis Kearney Agricultural Center	California Regulated Deficit Irrigation Program and Remote Sensing to Quantify Evapotranspiration	$563,000	$1,126,000
Prop 50 Water Use Efficiency Grants/04-05	San Joaquin County RCD	Mobile Lab & Irrigation Workshop in Spanish	$60,000	$127,560
Prop 50 Water Use Efficiency Grants/04-05	Anderson-Cottonwood Irrigation District	ACID Main Canal Modernization Project	$1,775,266	$1,815,266
Prop 50 Water Use Efficiency Grants/04-05	Amador Water Agency	Amador Transmission Project	$500,000	$15,032,281
Prop 50 Water Use Efficiency Grants/04-05	The Regents of the University of California Division of Agriculture and Natural Resources	Conserving Water and Improving Plant Health in Large Southern California Landscapes	$130,009	$170,680
Prop 50 Water Use Efficiency Grants/04-05	Contra Costa Water District	High Efficiency Toilet and Urinal Replacement Program	$657,447	$1,314,894
Prop 50 Water Use Efficiency Grants/04-05	City of Sacramento	Park Irrigation Infrastructure Improvement	$754,000	$897,000
Prop 50 Water Use Efficiency Grants/04-05	Metropolitan Water District of Southern California	Residential High Efficiency Clothes Washer Rebate Program	$1,660,000	$3,652,000
Prop 50 Water Use Efficiency Grants/04-05	Los Angeles County Waterworks District	Residential Water Use Audits Program	$386,640	$699,640
Prop 50 Water Use Efficiency Grants/04-05	Los Angeles County Waterworks District	CII Water Use Audits & Dedicated Landscape Meter Program	$108,681	$434,727
Prop 50 Water Use Efficiency Grants/04-05	Metropolitan Water District of Southern California	California Friendly Communities	$423,150	$577,150
Prop 50 Water Use Efficiency Grants/04-05	Metropolitan Water District of Southern California	High-Efficiency Toilet Rebate Program	$1,000,000	$1,840,000
Prop 50 Water Use Efficiency Grants/04-05	City of Port Hueneme	Citywide Meter Retrofit and System Audit Program	$345,324	$1,383,297
Prop 50 Water Use Efficiency Grants/04-05	Newhall County Water District	Residential ET Controller Rebate Program	$55,332	$221,329
Prop 50 Water Use Efficiency Grants/04-05	West Basin Municipal Water District	West Basin Municipal Water District Restroom Retrofit Project	$294,834	$589,668
Prop 50 Water Use Efficiency Grants/04-05	San Benito County Water District	Water Softener Rebate Program	$300,000	$605,560
Prop 50 Water Use Efficiency Grants/04-05	El Dorado Irrigation District	EID CII/Multi-FamilyLandscape Sub-Metering and ET Controller Installation Project	$83,098	$167,299
Prop 50 Water Use Efficiency Grants/04-05	Inland Empire Utilities Agency	Multi-Family ULFT Direct Install Program	$1,650,133	$4,086,792
Prop 50 Water Use Efficiency Grants/04-05	Electric and Gas Industries Association	Regional Resource - Efficient Clothes Washer Rebate Program	$1,534,342	$3,710,158

Program/Year Proposition 50 Water Use Efficiency	Applicant Agency	Project Title	Grant Amount	Total Project
Prop 50 Water Use Efficiency Grants/04-05	Municipal Water District of Orange County	Industrial Process Water Use Reduction Program	$404,801	$819,009
Prop 50 Water Use Efficiency Grants/04-05	L.A. Depart. Of Water & Power	Park Irrigation Efficeincy Program	$362,000	$1,140,970
Prop 50 Water Use Efficiency Grants/04-05	California Urban Water Conservation Council	Statewide Rebate Program for Cooling Tower Conductivity Controllers	$349,714	$955,714
Prop 50 Water Use Efficiency Grants/04-05	Los Angeles, City of	Large Landscape “Smart Irrigation” Program	$183,750	$371,170
Prop 50 Water Use Efficiency Grants/04-05	California Urban Water Conservation Council	Statewide Urban Water Agency One-Stop Rebate Program	$1,250,000	$2,691,000
Prop 50 Water Use Efficiency Grants/04-05	Los Angeles, City of	Cooling Tower Conductivity Controller Replacement Program	$350,000	$1,025,000
Prop 50 Water Use Efficiency Grants/04-05	West Sacramento, City of	Parks Irrigation Retrofit Program	$324,551	$324,551
Prop 50 Water Use Efficiency Grants/04-05	Biggs-West Gridley Water District	Regional Water Measurement Program	$50,000	$66,000
Prop 50 Water Use Efficiency Grants/04-05	Cathedral City, City of	Landscape Irrigation System Upgrade	$36,900	$91,350
Prop 50 Water Use Efficiency Grants/04-05	Richgrove Community Services District	Richgrove Water Meter Retrofit Program	$119,683	$119,683
Prop 50 Water Use Efficiency Grants/04-05 Subtotal			**$26,567,848**	**$62,025,846**

Program/Year Proposition 13 Water Use Efficiency	Applicant Agency	Project Title	Grant Amount	Total Project
Prop 13 Water Use Efficiency Grants/03-04	East Bay Municipal Utility District	ET Controller Installation Project	$1,660,725	$2,102,682
Prop 13 Water Use Efficiency Grants/03-04	Santa Clara Valley Water District	Targeted IrrigationSystem Hardware Upgrades	$100,000	$188,715
Prop 13 Water Use Efficiency Grants/03-04	City of Los Altos	ET Controller Installation in 6 City Parks	$50,000	$52,003
Prop 13 Water Use Efficiency Grants/03-04	City of Davis	Water Meter Installation-El Macero Subdivision	$377,844	$377,844
Prop 13 Water Use Efficiency Grants/03-04	Inland Empire Utilities Agency	Water Conservation Program - Inst. For Men and Assoc. Facilities	$2,059,555	$2,059,555
Prop 13 Water Use Efficiency Grants/03-04	Tulare County Water Works District	Alpaugh Water Meter Retrofit Program	$70,200	$70,200
Prop 13 Water Use Efficiency Grants/03-04	Metropolitan Water District of Southern California	ET Controller Installation Project	$1,778,700	$2,851,633
Prop 13 Water Use Efficiency Grants/03-04	Paradise Irrigation District	Main Replacement Project	$1,310,522	$1,470,239
Prop 13 Water Use Efficiency Grants/03-04	Santa Clara Valley Water District	Innovative High Efficiency Commercial Retrofits	$496,000	$658,607
Prop 13 Water Use Efficiency Grants/03-04	San Diego County Water Authority	X-Ray Film Processor Recirculating System	$623,500	$1,708,356
Prop 13 Water Use Efficiency Grants/03-04	East Bay Municipal Utility District	X-Ray Processor Recycling Capital Outlay Project	$152,400	$180,900
Prop 13 Water Use Efficiency Grants/03-04	Contra Costa Water District	Targeted Multi-Family Toilet Replacement Program	$203,670	$407,340
Prop 13 Water Use Efficiency Grants/03-04	San Diego County Water Authority	Commercial Landscape Incentive Program	$1,125,000	$2,452,500
Prop 13 Water Use Efficiency Grants/03-04	Montara Water & Sanitary District	Water Conservation Program (Toilets & Washers)	$190,000	$200,000
Prop 13 Water Use Efficiency Grants/03-04	Regional Water Authority	Large Landscape	$975,000	$1,071,429
Prop 13 Water Use Efficiency Grants/03-04	Placer County Water Agency	Water Line Replacement	$255,185	$510,370
Prop 13 Water Use Efficiency Grants/03-04	Yucaipa Valley Water District	High Efficiency Plumping Fixture Program	$98,900	$152,036
Prop 13 Water Use Efficiency Grants/03-04	Central Basin Municipal Water District	Enhanced Rebates and Incentives for Water Savings Devices	$780,000	$936,000
Prop 13 Water Use Efficiency Grants/03-04	East Bay Municipal Utility District	Regional Resources Efficient Clothes Washer Rebate	$2,190,375	$5,039,100
Prop 13 Water Use Efficiency Grants/03-04	City of Santa Monica	Comprehensive Medical Facility Retrofit Program	$126,300	$208,300
Prop 13 Water Use Efficiency Grants/03-04	Santa Barbara County Water Agency	CII Rebate Program	$268,600	$309,675
Prop 13 Water Use Efficiency Grants/03-04	City of Placentia	Tri-City Park Irrigation System Upgrade	$58,298	$100,798
Prop 13 Water Use Efficiency Grants/03-04	Los Osos Community Service Dist.	LOCSD Water Conservation Toilet Retrofit Program.	$500,000	$1,591,201

Program/Year Proposition 13 Water Use Efficiency	Applicant Agency	Project Title	Grant Amount	Total Project
Prop 13 Water Use Efficiency Grants/03-04	Long Beach Water Department	CII-School Zero Consumption Urinals Direct Installation	$168,625	$218,625
Prop 13 Water Use Efficiency Grants/03-04	Metropolitan Water District of Southern California	Residential High Efficiency Clothes Washer Rebate	$2,500,000	$3,666,666

Program/Year Proposition 13 Water Use Efficiency	Applicant Agency	Project Title	Grant Amount	Total Project
Prop 13 Water Use Efficiency Grants/02-03	East Bay Municipal Utility District	Pre Rinse Spray Head and Dishwasher Installation Program for Fast Food Industry	$482,081	$730,426
Prop 13 Water Use Efficiency Grants/02-03	Goleta Water District	Large Meter Project	$85,800	$132,000
Prop 13 Water Use Efficiency Grants/02-03	Inland Empire Utilities Agency	X-Ray Film Processor Retrofit Program	$230,000	$245,750
Prop 13 Water Use Efficiency Grants/02-03	Marina Coast Water District	Water Conservation System Rehabilitation Program	$959,029	$959,029
Prop 13 Water Use Efficiency Grants/02-03	Pasadena, City of	CII Zero Consumption Urinal Direct Installation	$300,000	$357,143
Prop 13 Water Use Efficiency Grants/02-03	Placer County Water Agency	Auburn System Leak Repair (Main Replacement)	$679,560	$1,121,690
Prop 13 Water Use Efficiency Grants/02-03	Rohnert Park, City of	Water Meter Retrofit Project	$1,276,548	$1,418,387
Prop 13 Water Use Efficiency Grants/02-03	San Diego County Water Authority	Coin Operated Multi Load Clothes Washer Voucher Incentive Program	$350,000	$536,320
Prop 13 Water Use Efficiency Grants/02-03	Upper San Gabriel Valley MWD	Olive Sports Park Model Water Efficient Landscape Project	$56,278	$94,938
Prop 13 Water Use Efficiency Grants/02-03	Bear Valley Comm. Service District	Residential ULFT Give-away	$44,000	$56,800
Prop 13 Water Use Efficiency Grants/02-03	Calaveras County Water District	Bear Creek Raw Water Pipeline Replacement	$1,925,000	$1,925,000
Prop 13 Water Use Efficiency Grants/02-03	Las Virgenes Municipal Water Dist.	Las Virgenes Municipal Water District	$145,000	$245,000
Prop 13 Water Use Efficiency Grants/02-03	Los Angeles Dept of Water & Power	Enhanced Rebates and Incentives for Water Savings Devices	$615,000	$1,230,000
Prop 13 Water Use Efficiency Grants/02-03	Pleasantimes Mutual Water Company	Water Meter Project	$49,000	$49,000
Prop 13 Water Use Efficiency Grants/02-03	Regional Water Authority	Large Landscape Irrigation System Incentive Program, 2002	$150,000	$166,667
Prop 13 Water Use Efficiency Grants/02-03	Regional Water Authority	Leak Detection and Repair Program	$386,750	$537,150
Prop 13 Water Use Efficiency Grants/02-03	Rio Dell, City of	WUE 2002 - Meter Replacement	$714,910	$714,910
Prop 13 Water Use Efficiency Grants/02-03	Santa Clara Valley Water District	Dedicated Landscape Meter Program	$100,000	$202,155
Prop 13 Water Use Efficiency Grants/02-03	Santa Clara Valley Water District	Water Softener Pilot Project	$60,000	$103,927
Prop 13 Water Use Efficiency Grants/02-03	Solano County Water Agency	Large Landscape ET Controller System Project	$195,000	$229,412
Prop 13 Water Use Efficiency Grants/02-03	Victor Valley Water District	Residential (ULFT) Replacement Project.	$51,233	$102,466

Program/Year Cost Proposition 13 Groundwater	Applicant Agency Storage Grants	Project Description	Grant Amount	Total Project
Prop 13 Groundwater Storage Construction Grants/ '03-'04	Golden Hills Community Service District	Existing facilities would be used for increased surface water recharge. The stored water would be conveyed through the proposed extraction well and transmission pipeline.	$740,500.00	$1,481,000.00
Prop 13 Groundwater Storage Construction Grants/ '03-'04	Arvin-Edison Water Storage District	Expand the Sycamore Spreading Works by 90 acres, expand the N1 Balancing Reservoir by 30 acres, and construct four recovery/extraction wells.	$2,000,000.00	$4,000,000.00
Prop 13 Groundwater Storage Construction Grants/ '03-'04	East Bay Municipal Utility District	Construct three aquifer storage and recovery (ASR) wells and new treatment, blending, transmission, and, monitoring of groundwater levels and subsidence in the East BayPlain sub-basin aquifer system.	$2,000,000.00	$21,650,000.00
Prop 13 Groundwater Storage Construction Grants/ '03-'04	Eastern Municipal Water District	Construct 15 recharge ponds and appurtenant facility additions and improvements inthe San Jacinto River channel.	$5,000,000.00	$10,757,731.00
Prop 13 Groundwater Storage Construction Grants/ '03-'04	Fresno Irrigation District	Construct 13 new recharge basins with diversion structures and delivery pipelines, eight recovery wells, and improvements to the canals delivering water to facilitates.	$4,615,072.00	$9,230,144.00
Prop 13 Groundwater Storage Construction Grants/ '03-'04	Inland Empire Utilities Agency	Recycled water conveyance facilities, recharge basin improvements resulting in better management of storm and dry season recharge.	$15,500,000.00	$81,701,011.00
Prop 13 Groundwater Storage Construction Grants/ '03-'04	Kern Delta Water District	Construct six new wells, modification of two existing wells, and construct approximately 660 acres of spreading basins along the Buena Vista canal.	$5,177,950.00	$10,355,900.00
Prop 13 Groundwater Storage Construction Grants/ '03-'04	Kings River Conservation District	Construct recharge basins and three extraction wells.	$2,737,753.00	$2,974,651.00
Prop 13 Groundwater Storage Construction Grants/ '03-'04	Pajaro Valley Water Management Agency	Construct a 22-mile pipeline, 17 supplemental wells along the pipeline, and a 26 mile coastal distribution system to deliver piped water to coastal properties.	$16,250,444.00	$124,587,157.00
Prop 13 Groundwater Storage Construction Grants/ '03-'04	Stockton East Water District	Construct a pipeline to convey surface water to existing and future recharge facilities and to deliver water that is recovered from groundwater storage using proposed	$3,700,630.00	$7,401,260.00
Prop 13 Groundwater Storage Construction Grants/ '03-'04	Sutter Extension Water District	Construct two groundwater production wells, a recharge program, monitoring program, and conjunctive use education program.	$1,510,897.00	$1,534,104.00
Prop 13 Groundwater Storage Construction Grants/ '03-'04	West Basin Municipal Water District	Expand and upgrade of the West Basin Water Recycling Plant to receive and treat more water and injection of recycled water for the seawater barrier.	$9,406,269.00	$33,918,000.00
Prop 13 Groundwater Storage Construction Grants/ '01-'02	Buena Vista Water Storage District	Construct three new extraction wells and associated conveyance pipelines to deliver additional banked groundwater.	$500,000.00	$1,000,000.00
Prop 13 Groundwater Storage Construction Grants/ '01-'02	United Conservation District	Construct a well field to manage groundwater storage in the Oxnard Forebay basin.	$1,423,595.00	$1,825,740.00
Prop 13 Groundwater Storage Construction Grants/ '01-'02	Cawelo Water District	Construction of diversion facilities from Poso Creek to Poso Reservoir for recharge.	$1,430,000.00	$2,978,178.00

Program/Year Cost Proposition 13 Groundwater	Applicant Agency Storage Grants	Project Description	Grant Amount	Total Project
Prop 13 Groundwater Storage Construction Grants/ '01-'02	City of Clovis	Construct four groundwater recharge basins on eight parcels.	$2,031,245.00	$4,273,745.00
Prop 13 Groundwater Storage Construction Grants/ '01-'02	Goleta Water District	Rehabilitate and convert existing wells to ASR wells to recharge and store Lake Cahuma water.	$1,802,019.00	$3,604,039.00
Prop 13 Groundwater Storage Construction Grants/ '01-'02	Kern Water Bank Authority	Construct 16 additional recovery wells and conveyance pipeline to route water to the California Aqueduct. Construct a lift station to convey water for recharge purposes.	$3,375,000.00	$6,750,000.00
Prop 13 Groundwater Storage Construction Grants/ '01-'02	North Kern Water Storage District	Provide water banking services to neighboring agencies and maintain groundwater resources underlying North Kern. New facilities include a turnout from the Friant-Kern Canal and four extraction wells.	$1,131,000.00	$2,626,487.00
Prop 13 Groundwater Storage Construction Grants/ '01-'02	Orange County Water District	Construction of the Groundwater Replenishment System that will collect highly treated municipal wastewater, which would normally be discharged to the ocean, and treat it to levels that exceed current drinking water standards, using membrane and disinfection processes. The water will then be injected underground to recharge aquifers.	$30,000,000.00	$487,000,000.00
Prop 13 Groundwater Storage Feasibility Study Grants/'01-'02	Madera Irrigation District	Evaluate potential increased recharge using Madera Lake and construction of additional recharge basins.	$150,000.00	$885,000.00
Prop 13 Groundwater Storage Feasibility Study Grants/'00-'01	Eastern Municipal Water District	Evaluate the technical, economic, and environmental issues associated with groundwater storage and identify a preferred alternative for a recharge and recovery scenario.	$200,000.00	$400,000.00
Prop 13 Groundwater Storage Pilot Projects/'00-'01	Three Valleys Municipal Water District	Construct a connection from an existing imported water pipeline to deliver supplementary water to an existing recharge basin.	$400,000.00	$500,000.00
Prop 13 Groundwater Storage Pilot Projects/'00-'01	Wheeler Ridge-Maricopa Water Storage Distric	Install five deep monitoring wells and one supply well to assist in the regulation of the District's State Water Project (SWP) supplies, provide capacity for the storage of surplus SWP water.	$1,333,094.00	$1,583,094.00
Prop 13 Groundwater Storage Pilot Projects/'00-'01	Pleasant Valley Water District	Study up to three groundwater storage banking/extraction locations and construct one full-scale groundwater storage pilot project.	$495,550.00	$590,550.00
Prop 13 Groundwater Storage Pilot Projects/'00-'01	Stockton East Water District	Development and two-year operation of a demonstration-scale groundwater recharge facility.	$1,341,000.00	$1,788,000.00
Prop 13 Groundwater Storage Pilot Projects/'00-'01	San Diego County Water Authority	Refine and verify the findings of a previously completed feasibility study and provide information needed to develop and design a groundwater storage project.	$1,250,000.00	$2,500,000.00
Prop 13 Groundwater Recharge Construction Loans Projects/'03-'04	Monte Vista Water District	Construct two new ASR wells, refurbishment of an existing well to an ASR well, and the rehabilitation of another well for injection.	$3,700,000.00 (Loan)	$4,667,136.00
Prop 13 Groundwater Recharge Construction Loans Projects/'00-'01	James Irrigation District	Construct a recharge basin and turnouts that will deliver water for recharge.	$1,578,950.00 (Loan)	$2,145,750.00
Proposition 13 Groundwater Subtotal			**$120,780,968.00**	**$834,708,677.00**

Program/Year SB 23 Water Use Efficiency Grants/2001	Applicant Agency	Project Title	Grant Amount	Total Project
SB 23 Water Use Efficiency Grants/01-02	Anderson Cottonwood	Main Canal Modernization	$100,000	$100,000
SB 23 Water Use Efficiency Grants/01-02	Cal-Poly-ITRC	Irrigation District Technical Assistance	$300,000	$600,000
SB 23 Water Use Efficiency Grants/01-02	Fresno CSU, CIT	Varability of Soil Salinity on Farms	$175,010	$281,410
SB 23 Water Use Efficiency Grants/01-02	Columbia Canal Company	On Farm Irrigation System	$152,823	$305,634
SB 23 Water Use Efficiency Grants/01-02	Glenn-Colusa ID	On-Farm Integrated Irrigation & Drainage Management	$100,000	$1,122,385
SB 23 Water Use Efficiency Grants/01-02	Golden State Irrigation Service, Inc	Sub-surface Drip Irrigation of Asparagus	$299,500	$800,167
SB 23 Water Use Efficiency Grants/01-02	Kern-Tulare WD	Automate Canal Structures	$310,000	$8,000,000
SB 23 Water Use Efficiency Grants/01-02	Lodi-Woodbridge Winegrape Comm	NPS Pollution Reduction in Vineyards	$217,440	$365,300
SB 23 Water Use Efficiency Grants/01-02	Lost Hills Water District	Service Area 5 Distribution System Improvements	$754,500	$894,900
SB 23 Water Use Efficiency Grants/01-02	Lost Hills Water District	Service Area 3 Distribution System Improvements	$572,100	$650,100
SB 23 Water Use Efficiency Grants/01-02	Modesto Irrigation District	On-farm Ditch & Cast-In-Place Replacement	$274,000	$548,000
SB 23 Water Use Efficiency Grants/01-02	Orland Unit Water Use Assoc	Regional Water Use Efficiency Project	$100,000	$296,800
SB 23 Water Use Efficiency Grants/01-02	Oroville-Wyandotte ID	OWID Palermo Canal Lining	$183,000	$251,000
SB 23 Water Use Efficiency Grants/01-02	Pajaro Valley Water Management Agency	On Farm Mobile Lab	$99,500	$132,905
SB 23 Water Use Efficiency Grants/01-02	Placer County Water Agency	Real-time Canal Flow Monitoring & Canal Lining	$662,744	$1,325,488
SB 23 Water Use Efficiency Grants/01-02	Reclamation District 108	GCID System	$100,000	$1,322,000
SB 23 Water Use Efficiency Grants/01-02	West Stanislaus RCD	Irrigation Management and Dormant Spray Reduction	$160,523	$330,598
SB 23 Water Use Efficiency Grants/01-02	USDA/Ag Reserch	Salt-Tolerant Crops Evaluation	$69,600	$69,600
SB 23 Water Use Efficiency Grants/01-02	West Hills Comm College District	Sub-basin Level Water Measurement Program	$100,000	$100,000
SB 23 Water Use Efficiency Grants/01-02	Western Canal Water Dist	WCWD Water Use Efficiency Project	$265,524	$285,524
SB 23 Water Use Efficiency Grants/01-02	San Joaquin Valley Drainage Authority	SW Stanislaus Co Regional Drainage Water Management	$616,200	$848,138
SB 23 Water Use Efficiency Grants/01-02	WaterTech	Irrigation Scheduling	$200,000	$200,000
SB 23 Water Use Efficiency Grants/01-02	Alameda Co. Water Dist.	ACWD Schools & Water Conservation Program	$125,000	$256,700

Program/Year SB 23 Water Use Efficiency Grants/2001	Applicant Agency	Project Title	Grant Amount	Total Project
SB 23 Water Use Efficiency Grants/01-02	Aquacraft, Inc.	Demonstration of Water Conservation in Urban Supermarkets	$126,000	$180,000
SB 23 Water Use Efficiency Grants/01-02	Blue Planet Foundation	WaterWise Resource Action Program	$38,000	$58,245
SB 23 Water Use Efficiency Grants/01-02	Calif. Water Awareness Campaign	Public Information Program	$250,000	$1,350,000
SB 23 Water Use Efficiency Grants/01-02	CalPoly State University-ITRC	Efficient Landscape Water Program	$244,000	$244,000
SB 23 Water Use Efficiency Grants/01-02	Contra Costa Water Dist.	A Straight Flush- Commercial ULFT Replacement	$150,000	$374,000
SB 23 Water Use Efficiency Grants/01-02	El Dorado Irrigation Dist.	ULFT Rebates for Low-Income Residents	$60,000	$104,300
SB 23 Water Use Efficiency Grants/01-02	Elect. & Gas Indust. Assoc. (EGIA)	Regional High-Efficiency Washing Machine Rebate	$1,750,875	$4,405,605
SB 23 Water Use Efficiency Grants/01-02	Environmental Policy Center	California Water Conservation Support Network	$115,000	$210,000
SB 23 Water Use Efficiency Grants/01-02	Expert, Inc.	Community Water Education & Training	$360,000	$390,000
SB 23 Water Use Efficiency Grants/01-02	Irvine Ranch Water Dist., et al.	Joint Agency X-Ray Processor Retrofit	$13,698	$41,698
SB 23 Water Use Efficiency Grants/01-02	Metropolitan Water Dist. of S. CA	New Courses for Bilingual Landscape Education	$100,000	$150,000
SB 23 Water Use Efficiency Grants/01-02	Metropolitan Water Dist. of S. CA	High-Efficiency Clothes Washer Rebates	$925,000	$1,500,000
SB 23 Water Use Efficiency Grants/01-02	Metropolitan Water Dist. of S. CA	Commercial Rebates Save Water-Save a Buck	$34,000	$60,000
SB 23 Water Use Efficiency Grants/01-02	Munic. Water Dist. Of Orange Co.	Water Softener Pilot Program	$100,000	$357,005
SB 23 Water Use Efficiency Grants/01-02	Pacific Institute	Waste Not Want Not: Potential for Urban Water Conservation	$72,500	$145,000
SB 23 Water Use Efficiency Grants/01-02	Pittsburg, City of	Save Our Delta System	$50,000	$100,000
SB 23 Water Use Efficiency Grants/01-02	Regents of University of CA	Water Wise Demonstration Landscape	$92,774	$277,663
SB 23 Water Use Efficiency Grants/01-02	Rose Bowl Op. Co.	Brookside Golf Course Water Management Project	$90,000	$228,100
SB 23 Water Use Efficiency Grants/01-02	San Diego Co. Water Authority	High-Efficiency Clothes Washer Voucher Program	$300,000	$873,500
SB 23 Water Use Efficiency Grants/01-02	San Juan WD - Water Forum	Sacramento Water Use Efficiency	$100,000	$100,000
SB 23 Water Use Efficiency Grants/01-02	Santa Barbara Co. Water Agcy.	Weather Trak ET Controller	$100,000	$351,325
SB 23 Water Use Efficiency Grants/01-02	Santa Clara Valley Water Dist.	Landscape and Ag Area Measurement & Water Use Budgets	$406,000	$7,234,570
SB 23 Water Use Efficiency Grants/01-02	Water Education	Water Conservation & Recycling Awareness Initiative	$168,675	$241,593
SB 23 Water Use Efficiency Subtotal			**$11,583,986**	**$38,063,253**

SELECTED REFERENCES

California Department of Water Resources. July 2006. Progress in Incorporating Climate Change into Management of California's Water Resources.

California Department of Water Resources. December 2005. California Water Plan Update 2005.

California Department of Water Resources. December 2000. Critical Water Shortage Contingency Plan, Governor's Advisory Drought Planning Panel.

California Department of Water Resources. July 2000. Preparing for California's Next Drought, Changes Since 1987-92.

Congressional Research Service. September 2005. Klamath River Basin Issues and Activities: An Overview.

Intergovernmental Panel on Climate Change. 2007. Fourth Assessment Report.

National Research Council. 2007. Evaluating Progress of the U.S. Climate Change Science Program, Methods and Preliminary Results.

National Research Council. 2007. Colorado River Basin Water Management, Evaluating and Adjusting to Hydroclimate Variability.

U.S. Bureau of Reclamation. November 2007. Final Environmental Impact Statement, Colorado River Interim Guidelines for Lower Basin Shortages and Coordinated Operations for Lakes Powell and Mead.

U.S. Department of Agriculture, Farm Services Agency. January 2007. Fact Sheet, Emergency Disaster Designation and Declaration Process.

ACRONYMS

AF	Acre-Feet
CALFED	California (CAL) and Federal (FED) Program for Bay-Delta Activities
CCSP	Climate Change Science Program
CDPH	California Department of Public Health
CRWA	California Rural Water Association
CVP	Central Valley Project
CVPIA	Central Valley Project Improvement Act
DWR	Department of Water Resources
ENSO	El Niño Southern Oscillation
ESA	Endangered Species Act or Emergency Services Act
ICS	Intentionally Created Surplus
IPCC	Intergovernmental Panel on Climate Change
MAF	Million Acre-Feet
MWD	Metropolitan Water District
NEPA	National Environmental Policy Act
NIDIS	National Integrated Drought Information System
NASA	National Aeronautics and Space Administration
NOAA	National Oceanic and Atmospheric Administration
NRC	National Research Council
NWS	National Weather Service
OES	Office of Emergency Services
PPM	Parts Per Million
QSA	Quantification Settlement Agreement
ROD	Record of Decision
SCWA	Sonoma County Water Agency
SNWA	Southern Nevada Water Authority
SOI	Southern Oscillation Index
SWP	State Water Project
TAF	Thousand Acre-Feet
TMF	Technical, Managerial, Financial (capacity)
USBR	U.S. Bureau of Reclamation
USDA	U.S. Department of Agriculture
USEPA	U.S. Environmental Protection Agency
USFWS	U.S. Fish and Wildlife Service
UWMP	Urban water management plan
WGA	Western Governors' Association

Department of Water Resources
P.O. Box 942836
Sacramento, CA 94236-0001